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Research Articles

Establishing a GIS toolbox to access urban verticality

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ABSTRACT

Cities today face the pressing challenge of meeting rising housing demand while preserving scarce land and environmental resources. Vertical extension presents a sustainable strategy to densify urban areas, minimizing outwards expansion and associated environmental impacts such as land take, habitat loss, and increased infrastructure demands. This study presents an innovative, user-friendly geospatial model designed to quantify the legal potential for vertical extension, demonstrated utilizing the city of Lüneburg, Lower Saxony, Germany as case study. Co-developed with local stakeholders and grounded in standardized data, the toolbox empowers planners and municipalities to independently explore, analyse, and visualize densification opportunities tailored to their specific context. By transforming complex spatial data into actionable insights, the approach offers a data-driven foundation to rethink urban planning and guide sustainable urban development.

1. Introduction

Urban areas across Germany, particularly in metropolitan regions such as Hamburg and Berlin, are experiencing increasing development pressure due to housing shortages and land scarcity [1–3]. Expanding cities drive the demand for space, especially for housing [4,5]. However, land scarcity demands balancing the dual objectives of land and environment conservation with the provision of additional space for building and development [6,7]. This ambiguity was emphasised by the German Land Saving Target, aiming to reduce daily land consumption to less than 30 ha by 2030, which was prepared by the federal government and implemented on a state as well as municipal level. Simultaneously, the climate protection plans by the former German government and the European Union served as national strategic framework targeting an overall net zero land consumption by 2050 through circular land economy [8]. In contrast, the goal to tackle the housing crisis was to build 400.000 new apartments per year [9]. Even though these targets are no longer explicitly stated in the coalition contract of the new German government of 2025, a general emphasis has been put on modernisation, inner development and strengthening affordable as well as sustainable housing (construction). This is to be achieved through targeted incentives, streamlined planning and approval procedures, as well as revisions to planning and building regulations [10]. The German Government recently passed an amendment to the building law aimed at accelerating building projects by allowing greater regulative flexibility (“Bau-Turbo”, English: “Building turbo”) [11]. In this context, urban planning has increasingly focused on efficient and sustainable land use strategies. Rather than expanding outward leading to urban sprawl, fragmented infrastructure, increased land consumption EEA, Foen, [12,13]and ecological challenges [14], the emphasis has shifted towards densification within existing urban boundaries [15,16].

One promising approach to literally square that circle is vertical building or vertical extension [17]. This involves adding additional floors to existing buildings [18]or demolishing structures and replacing them with higher rising buildings [19]. By avoiding land consumption and urban sprawl external pressure on green and agricultural spaces is reduced [20,21]. Vertical extension allows cities to accommodate growth without constructing entirely new infrastructure networks, as existing roads, utilities, and public services can often be utilised and incrementally adapted to support additional housing [22,23]. Thereby, vertical extension contributes to reducing resource consumption and greenhouse gas emissions by minimising transportation distances and promoting the shared use of infrastructure [24]. Additionally, degradation of city and village centres can be reduced, keeping them vibrant and populated Brandt and Schmitt [25].

In Germany, spatial planning and urban development are guided by

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the concept of “Inner development before external development”. Through the utilisation of already developed and integrated sites with new concepts designation of new building areas and further land use change are minimised. The principle is also anchored in the German building code as well as in the German regional planning act [26]. Tichelmann et al. [3] identified a total potential of 2.3 to 2.7 million additional residential units through vertical extension in Germany, thus highlighting vast opportunities for actionable measures and localised analyses. Numerous studies around the globe have examined vertical extension as a strategy for urban densification.

While these works primarily focus on structural feasibility, design innovation, or architectural performance, most remain confined to the building or neighbourhood scale and rarely apply Geographic Information Systems (GIS)-based methods for spatially explicit analysis [27]. Various studies map or model vertical extension in urban areas, predominantly in metropolitan cities (e.g. [28–30]. However, research that quantitatively integrates regulatory, and spatial dimensions to assess vertical extension potential at the city scale remains limited. Amer et al. [31] developed a GIS based three-phase decision-making framework integrating urban policy analysis, engineering feasibility, and architectural evaluation to assess the potential of roof stacking for urban densification. The results showed that vertical extensions could accommodate 30% of Brussels projected population growth by 2040. [32] proposed a GIS-based assessment framework to evaluate vertical extension feasibility under the UK's permitted development rights. Based on building data, zoning restrictions, and regulatory filters, the study estimated that Sheffield could house up to 175.000 additional residents through vertical extensions.

Such geospatial tools and models are primarily designed for expert users and can be one-time snapshots. Municipalities with limited resources and capacities are therefore often unable to fully utilise these tools to independently and continuously analyse their urban environments [33,34]. This creates a barrier to self-sufficient planning and decision-making in the context of urban planning. However, GIS tools that generate spatial assessments have become essential instruments in urban planning, enabling city planners to identify, evaluate, and prioritise development opportunities amid increasingly complex data environments van Maarseveen et al. [35]. Consequently, there is a pressing need for the development of accessible, integrated and user-oriented geospatial tools supporting administrations in striving for data-driven transformation and planning. Hereby, administrative institutions are empowered to more independently make spatial data tangible. Such approaches serve as stepping stones and allow for grounded decision making based on local characteristics and needs (e.g. [36,37].

Our study aim is twofold. The first aim is to introduce a geospatial model for assessing vertical extension potential of existing buildings from a regulative perspective, utilizing the city of Lüneburg, Lower Saxony, Germany as a case study. The model serves as an initial evaluation, allowing for a city-wide overview of potential. The second aim is to provide an easy to use, automated and comprehendible geospatial toolbox for the Lüneburg city administration allowing for own output creation and further analysis. Ultimately, we target fostering data-driven urban planning, supporting decision-makers and urban planners. By doing so, the study contributes to steering sustainable urban densification strategies, reducing land consumption, and, as a result environmental impacts, while optimizing existing infrastructure and tackling development pressure.

In the methods section we describe the case study and our approach. In the result section we present the tools’ functionality as well as output with default settings. In the light of the research objectives, we then discuss the tools’ utility alongside the model approach as well as implications for planners and decision-makers, ending with final conclusions.

2. Methodology

2.1. Case study

This study was carried out as part the transdisciplinary research project SUSTIL.[1] The project was carried out from 2020 until 2025 and was part of national initiative “Stadt-Land-Plus” funded by the German Ministry for Education and Research (BMBF)[2] with 22 projects in five clusters. As part of the cluster “Regionale Gerechtigkeit” (English: Regional justice) the goal was to collaboratively identify land use demands of actor groups using scenario planning. Subsequently, measures were co-developed to tackle land use conflicts in together with local project participants from administration, nature conservation, society and industry the district and city of Lüneburg. Out of this process the demand for the analysis of vertical extension potential in the city arose. The presented study was conducted in close cooperation with the city administration of Lüneburg as well as the LüWoBau GbmH, a local public housing company.

The city of Lüneburg (see Fig. 1) inhabits 77.511 people (41% of the district’s inhabitants; status as of December 31th, 2023)[38]in an area of 7050 ha, while the rest of the district is predominantly rural in character. The city, located in the district of Lüneburg south-east to the city of Hamburg, is part of the Hamburg metropolitan region within an economically strong network and an overall population growth (see Fig. 2) [39], which is expected to reach nearly 80.000 by 2030 [38].

Furthermore, the city serves as district capital and hosts a university with over 11.000 students and staff members [40]. Therefore, the housing market and housing demand is increasingly pressured [41]. The city of Lüneburg contains 40.478 residential units distributed across residential and non-residential buildings, with 35% consisting of single- and two-family houses and 65% comprising multi-family houses [38]. With 43%, the majority of residential buildings were built between 1949 and 1978. 21% were built before 1949 and 36% after 1978 [41,42]. Overall building projects have stalled since the 1990 s. Yet a recent increase has shown, with 285 new residential units built in 2024 (see Fig. 3) [43]. Projections however assume a demand of 3.490 newly built residential units until 2040, which originates not only in population growth but also in the rising demand of single and senior citizens apartments in the course of demographic change [41].

Hence, the city offers a compelling context for analysing vertical building potential due to its heterogeneity of old town buildings, residential areas from various time frames, including single homes as well as smaller up to larger multi apartment buildings, industrial and commercial zones. The location within the metropolitan region of Hamburg makes it representative of a city within a growing region, experiencing development pressure. Compared to larger cities and metropolises, the medium city size of Lüneburg permits a more complete examination of its entire area. Conducting this study within the transdisciplinary SUSTIL project enabled the development of a tool tailored directly to the needs and preferences of target users.

2.3. Building regulation law in Germany

In Germany maximum regulatory allowable building (floor level) height is regulated primarily through the building regulation law. Defined in the German Building Code (Baugesetzbuch, BauGB), it determines which and how buildings can be modified or expanded. Two

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[1] Full name: *Scenarios for the Implementation of the United Nations’ Sustainable Development Goals in the City and District of Lüneburg: Implications for Land Use Management.*

[2] The new German Government of 2025 restructured the Bundesministerium für Bildung und Forschung (BMBF) into the Bundesministerium für Forschung, Technologie und Raumfahrt (BMFTR) (Englisch: Ministry for Research, Technology and Aerospace).

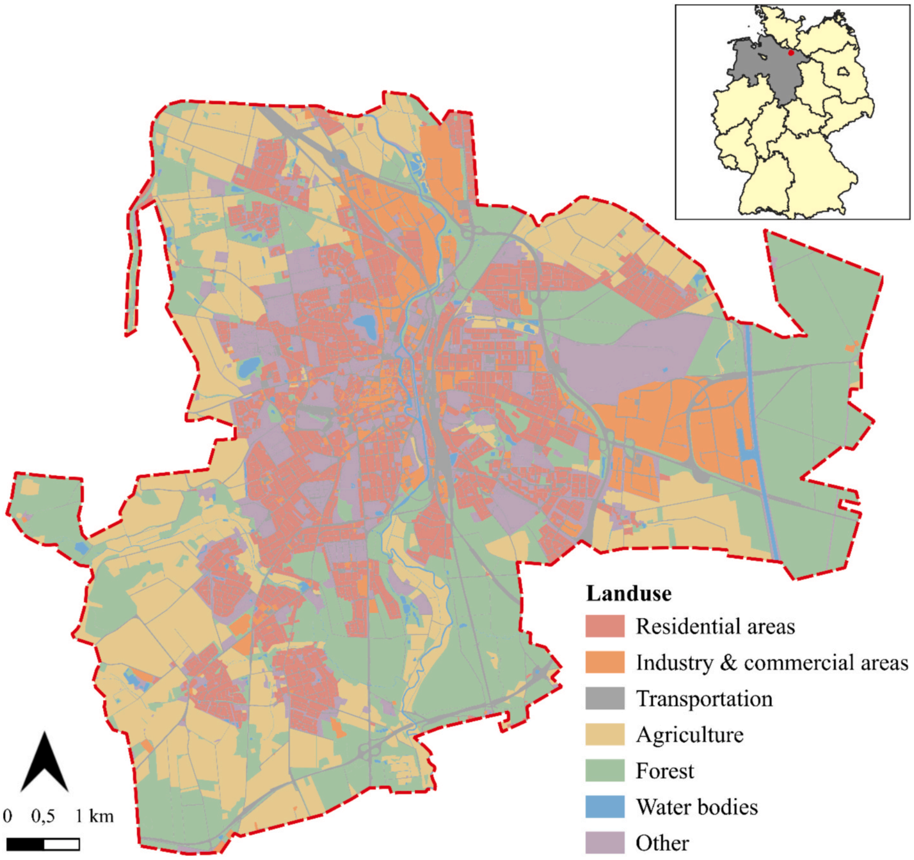

Fig. 1. Hanseatic city of Lüneburg, Federal state of Lower Saxony, Germany (Data sources: Administrative Areas 1: 5 000 000 VG5000, German Federal Agency for Cartography and Geodesy 2022; ALKIS (Amtliches Liegenschaftskatasterinformationssystem, Englisch: Authoritative Real Estate Cadastre Information System, is the official cadastral system used in Germany to manage land and property data) land use, Federal state office for geoinformation and land surveying of Lower Saxony (LGLN) 2024).

key regulative frameworks are relevant when assessing vertical extension potential, on which our study is based on: (1) For areas with development plans building height is specified by § 8–10 of the German Building Code. Development plans are binding zoning regulations that define specific building and land-use parameters within designated areas of a municipality. Based on broader land-use plans, their primary purpose is to regulate land use, building extents and heights, density levels, and construction guidelines while balancing urban growth with environmental and infrastructural considerations. Central attributes are maximum building height in meters and number of floors, floor area ratio (Geschossflächenzahl, GFZ), which caps total usable floor space relative to plot size, and the building coverage ratio (Grundflächenzahl, GRZ), which restricts land parcel coverage and indirectly affects density. Land-use categories, such as residential or commercial, further dictate the usage restrictions. (2) In areas without specific development plans § 34 BauGB applies. Unlike designated zoning areas where precise height restrictions and land-use parameters are explicitly defined, § 34 BauGB relies on a contextual assessment of the surrounding built environment. New buildings or modifications, including vertical extensions, must align with the character of the existing neighbourhood to ensure architectural continuity and urban harmony. Therefore, a construction project is permissible if it “fits within the characteristics of the surrounding area”. This includes considerations of building height, floor area and volume, structural alignment with neighbouring buildings and use and function (e.g., residential, commercial, mixed-use). Furthermore, requirements for healthy living and working conditions must be sustained. The local scene must not be compromised. This case-by-case evaluation therefore varies depending on interpretation, municipal guidelines, and even individual regulative disputes. Municipalities are hereby enabled for flexible and adaptable planning. Also, coherency with the existing cityscape is ensured. On the other hand, case-by-case assessments of §34 BauGB result in certain degree of subjectivity or lack of clarity what constitutes a harmonious or acceptable modification. This leads to a certain variance in the interpretation of the law in practice and needs to be taken into consideration when developing and evaluating standardised urban planning assessments.

In order to address the tense housing market in Germany, the new German Government passed an amendment to the building law, which came into force at 30st of October 2025. This recently introduced “Bau-Turbo” (§ 246e BauGB) (English: Building turbo) functions as an experimental clause designed to accelerate residential construction. It permits municipalities to deviate from the existing building code (BauGB) and associated urban planning statutes, thereby creating new building rights without the need to draft or amend development plans. This enables, for example, the vertical or lateral extension of existing buildings and the construction of new housing within inner-city areas, even when development plans do not conform to the prevailing urban fabric. Complementary amendments to §§ 31(3) and 34(3b) BauGB pursue similar objectives. § 31(3) allows additional residential development within areas covered by existing development plans, including through vertical extension. § 34(3b) extends these flexibilities to unplanned inner areas. It is essential to highlight, that in both cases, municipal consent remains a prerequisite. Unlike the temporary experimental clause of § 246e BauGB, these adjustments are permanent, aiming to facilitate the practical implementation of densification measures and lower administrative barriers to housing development. Overall, all amendments supplement established building regulations rather than overruling them or making them obsolete. Hence, it remains a

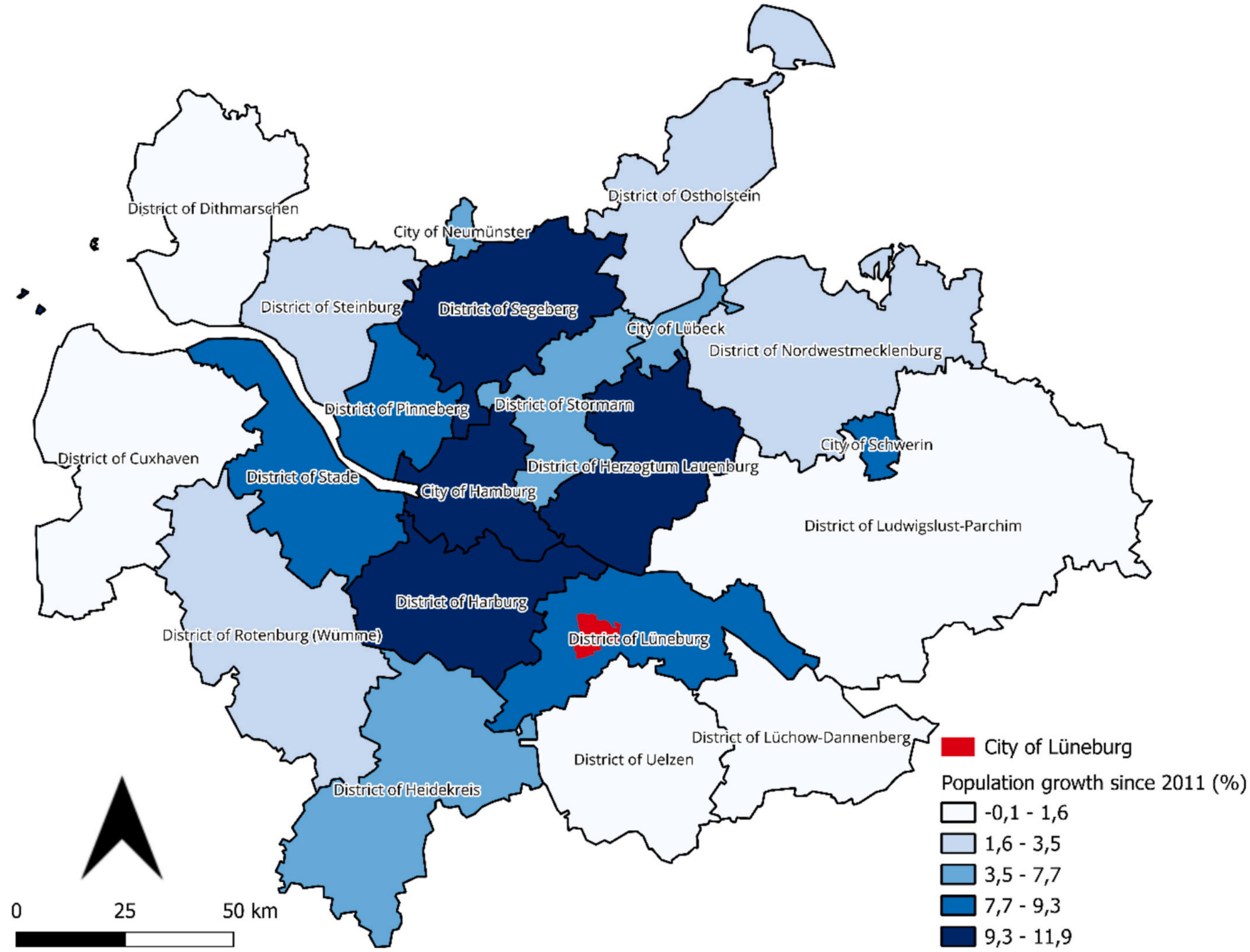

Fig. 2. Metropolitan region of Hamburg – Population growth since 2011 (Data sources: Administrative Areas 1: 5 000 000 VG5000, German Federal Agency for Cartography and Geodesy 2022; Statistical Office for Northern Germany, updated based on the 2011 census 2023).

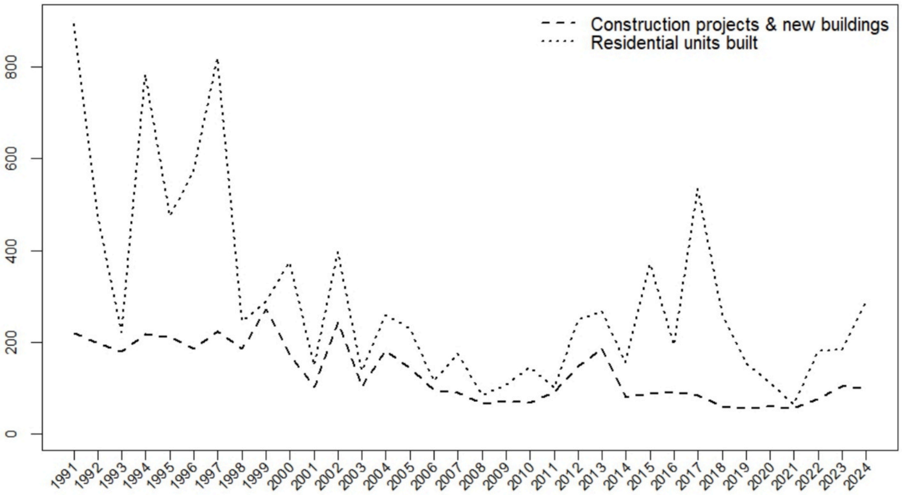

Fig. 3. Number of construction projects & new buildings and new residential units built in the city of Lüneburg per year from 1991 to 2024 (Data). Source: LSN, [43]

matter of which regulation is to be applied, when assessing vertical extension potential.

Importantly, the “Bau-Turbo” does not devalue our approach. On the contrary, it reinforces the need for data-driven instruments that enable municipalities to spatially identify and assess new development opportunities and as a result decided whether to apply such special regulations. Our geospatial toolbox delivers the analytical foundation to evaluate where such measures are feasible and sustainable by translating regulatory potential into spatially explicit, evidence-based decision support.

2.4. Modelling approach and development

Our modelling approach is based on the underlying assumption that potential is existent when buildings have not reached the maximum regulatory allowable building height. For our model, we adopted a two-pronged approach to address these regulative frameworks individually. The first component addresses areas with existing development plans, where the permissible number of floors or building height can be directly extracted from the plan specifications. Here, we calculate the difference between allowable height and the real building height per building within each available development plan. The second component pertains to areas without development plans – §34 BauGB areas. In context of German planning law, our chosen approach operates on the principle that buildings with lower heights relative to the highest building aggregated in a determined unit of observation, representing the surrounding area, have potential for further development. There is no clear quantitative or unified definition of what constitutes the "surrounding area" and is typically evaluated on a case-by-case basis. In the light of our standardisation approach, we chose street parcels as our defining units of observation. The potential of each building is calculated as the difference to the highest building of the respective unit of observation. Even though they can serve as height defining building, landmarks, monumental and protected buildings are excluded from receiving a potential value. A detailed description of the model logic and calculations for each tool can be found in appendix A and B.

Notably, roof geometry is an important factor influencing the feasibility and cost of vertical extensions. For example, generally flat roofs can be considered more suitable from such a perspective. However, this parameter was not included in the model, which is rooted in our model approach. Firstly, the utilised base building data provides only simplified roof representations without sufficient detail to reliably differentiate between flat, pitched, and complex roof types. Incorporating roof geometry based on such generalised data would have introduced a layer of uncertainty and inconsistency into the results. To incorporate roof geometry much more complex data and as a result even more complex models are required. This however, was not part of our approach of creating a simple and easily adaptable model. Secondly, since the model primarily aims to assess vertical extension potential from a regulatory perspective rather than structural or architectural feasibility, roof geometry was excluded to maintain simplicity and transferability. Nevertheless, the output data still includes the roof type attribute, which allows users to filter results by roof type for more nuanced analyses.

Due to the transdisciplinary nature of the SUSTIL project, the development of the model and toolbox was carried out in close collaboration with multiple actors, particularly representatives of the city administration of Lüneburg. This collaborative process ensured both practical applicability and institutional relevance of the tools. The collaboration focused on two main objectives: Firstly, aligning tool design and functionality with the operational requirements and digital infrastructure of the city administration, and secondly, ensuring accessibility and usability for non-expert users, while minimising tool maintenance and workload requirements for the user. Representatives from the city's geodata department, urban planning department, data protection office, and the Department of Climate and Sustainability were actively involved throughout the development process. Regular feedback sessions were conducted to discuss data structures, model parameters, and interface design. Throughout the development phase the tool was continuously tested within the IT-systems of the city administration. This iterative exchange enabled continuous refinement of the toolbox and facilitated its seamless integration into the city's existing geo-information systems. A key design principle was to maintain model simplicity without compromising analytical value. The aim was not to deliver a fully finalised product, but rather a flexible, adaptable first-step tool that empowers municipal users to independently modify, extend, and apply it to evolving planning needs. This approach supports long-term usability and fosters administrative ownership of the digital instruments developed. By the end of 2024 the final toolbox was handed over to the GIS department of the city of Lüneburg.

Data.

Required data are development plans, which were provided by the city administration as standardised X-plan GML data format according to the XPlanung standard (XPlan) serving as Germany wide exchange format for spatial data [44]. At date of the model development the city administration was still in the process of converting the remaining development plans according to X-plan. 53 from a total of 249 development plans were available for analysis. Further geo-data required were (historical) monuments and landmarks and street and building parcels extracted from the open data ALKIS data set ("Amtliches Liegenschaftskatasterinformationssystem", English: Authoritative Real Estate Cadastre Information System) [45]. Real building height was extracted from the 3D-building model Level of Detail 1 (LoD1) available as well as open data by the state office for geoinformation and land surveying of the federal state Lower Saxony, Germany (Landesamt für Geoinformation und Landesvermessung Niedersachsen, LGLN) [46]. Detailed information regarding input data can be found in appendix A.

2.5. Validation and Robustness

To approximate the reliability and accuracy of both models a stratified exemplary validation was conducted. The detailed methodology and results of this validation are provided in appendix D.

3. Results

The final tools for areas covered by development plans and areas governed by § 34 BauGB were implemented as ArcGIS Pro geoprocessing model toolbox. ArcGIS Pro currently serves as primary GIS software for the city administration of Lüneburg. The tool masks can be viewed in appendix A.

The required inputs for tool 1 analysing areas covered by development plans are:

- Output saving location as geodatabase
- Folder path containing development plans in GML format
- Data path for 3D-building model Lod1 as shape file
- Parameter: "Difference (m) ground level to ground floor" to account for plinths; default is 0
- Parameter: "Minimal area (m^2) to include"; default is 30
- Parameter: "Floor level height" – assumed height per floor level in meter; default is 3

For tool 2 regarding § 34 BauGB areas required inputs are:

- Output saving location as geodatabase
- Data path for total area with building plans as shape file
- Data path for ALKIS real use as shape file
- Data path ALKIS parcels as shape file
- Data path for 3D-building model Lod1 as shape file
- Parameter: "Minimal area (m^2) to include"; default is 30
- Parameter: "Height difference in meter between highest and second highest Building, when to use second highest building as reference" – to account for outliers; default is 4

Once file paths are set and required parameters defined, users can execute the tools. Processing using our data set takes approximately 10 to 30 s. Each output is stored in the set geodatabase as geopackages. For Tool 2, in addition to the main output two supplementary geopackages are generated containing landmarks and protected buildings as well as building polygons unassignable to street parcels due to enclosure by other buildings or ALKIS data inconsistencies. After finishing processing, the output is loaded in the current ArcGIS Pro project. The output data contains various attributes to allow for more tailored assessments and filtering based on user-defined preferences. Notable examples are feature ID, building function, building height attributes, such as eaves and ridge height and polygon area. In the case of tool 1 regulatory attributes, such as allowable floor number and height, as well as calculated potential for additional floor levels and height are included. For tool 2, additionally street parcel ID, to which a building polygon is assigned to, as well as the difference to the highest reference building for eaves and

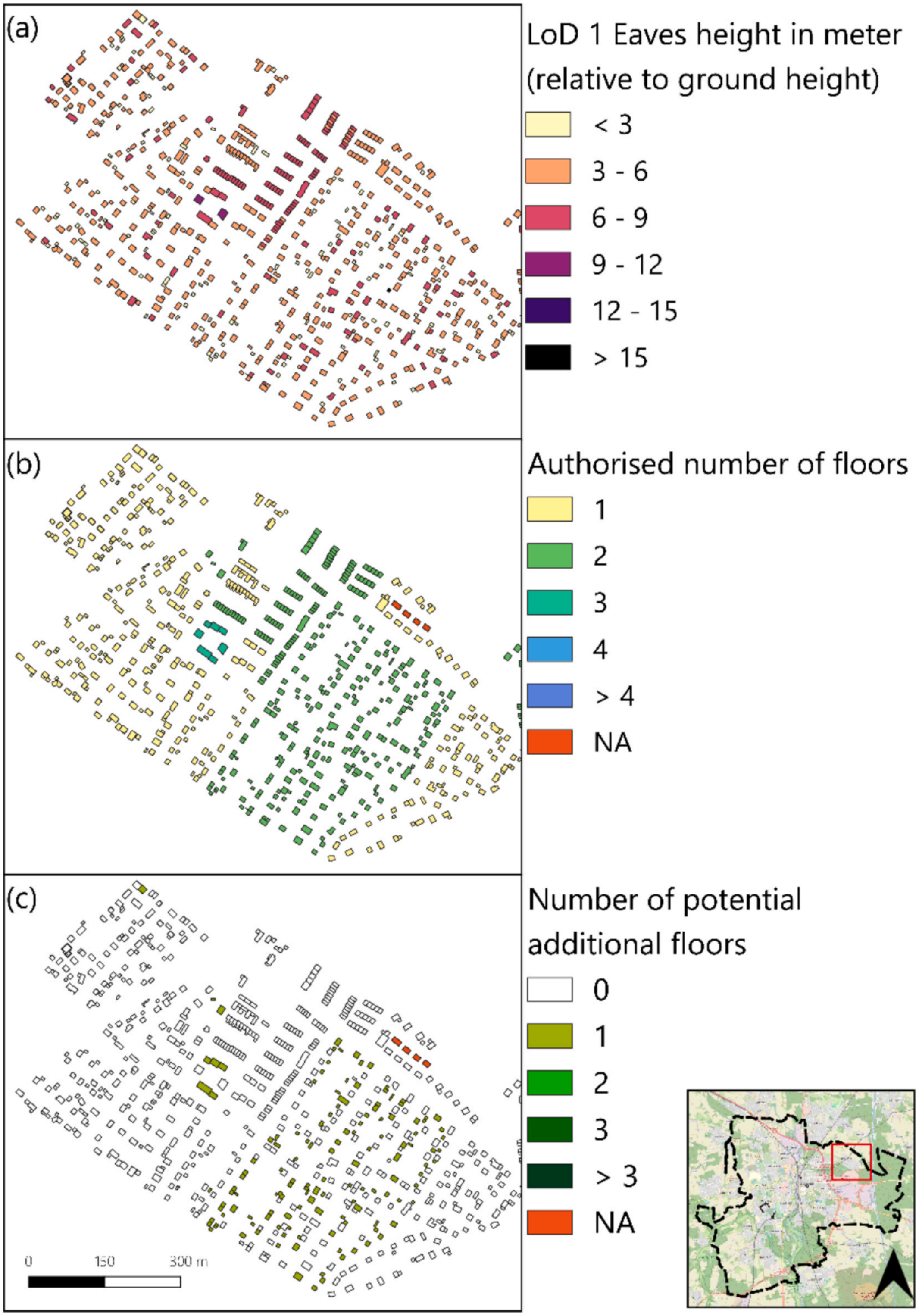

Fig. 4. Example map (Ebensberg, Hanseatic city of Lüneburg) of (a) the LoD1 building model, (b) allowable floor number derived from development plans and (c) calculated potential for additional number of floor levels using default tool settings (basemap © OpenStreetMap).

ridge respectively are provided. Thus, the model and its tools adopt a holistic approach. All building types are considered during processing, with the only filter being user-specified in subsequent output analysis. Based on this approach secondary buildings, such as garages or small structures, which may not always be relevant for extension potential assessments, are included as well and need to be considered during the evaluation. Overall, the tools aim at supplying the user with sufficient versatility for evaluating output in order to derive practical insights for further analysis and data-driven decision making.

In the following section we show how output in tandem with provided attributes can generate nuanced results. These results were produced using default settings and serve primarily as examples of the tools' functional capacity to the case study of Lüneburg. They illustrate how standardised, scalable assessments of vertical densification potential can be operationalised to support evidence-based urban development strategies tailored to user demand. In our output assessment we only consider full floors. Also, in accordance with the assumed default floor level height, we chose a categorisation of 3-meter ranges for assessing potential, where < 3 m in the output accounts for no potential. A full default output data set can be found in the supplementary material. Validation results for both tool outputs can be found in appendix B.

3.1. *Development plan areas*

Within the city of Lüneburg, 63% of all building polygons are located within zones governed by development plans. However, only 53 out of 249 development plans (covering 18% of buildings within development plan areas and 11% of all citywide buildings) were available for analysis at the time. Notably, 95% of the accessible plans included floor-level information, while only 8% contained explicit height attributes in meters, reinforcing the emphasis on floor-based potential calculations.

Focusing on buildings larger than 30 m^2, 13% of polygons (covering 10% of the cumulative area) exhibit a potential for the addition of at least one floor level. 24% of those polygons fall into the 50–100 m^2 range and 45% in the 30–40 m^2 range, indicating that the latter are secondary buildings. When filtering for residential buildings exclusively, only 3% of polygons demonstrate extension potential, 4% of the polygon area sum. This suggests that development plans are already fully utilised regarding buildable height. Nonetheless, 74% of residential polygons with potential have a minimum of 40 m^2, highlighting the presence of small opportunities within residential zones. Fig. 4 shows an example of one analysed development plan.

3.2. *§ 34 areas BauGB*

Buildings outside of development plan areas account for 38% of the total building polygons in the city of Lüneburg. Following the automatic exclusion of landmarks and protected structures[3] (19%) and assignment errors (5%), the analysis revealed that most buildings are associated with a single street parcel (77%), facilitating a straightforward reference height determination.

When assessing potential based on eaves height, 63% of analysed polygons ($\geq$30 m^2) display a minimum height difference of 3 m relative to the tallest building in their respective street parcels, with the majority in the 3 to 6 m range. Fig. 5 shows such an exemplary extract of areas without development plans. Similar results can be found when assessing potential using ridge height, where 65% show potential. Accounting for polygons potentially linked to multiple street parcels and selecting the lowest reference value as a conservative approach, potential is found in 43% of all § 34 BauGB buildings (4.479 polygons covering 463.769 m^2 in sum). Focusing on larger buildings ($\geq$50 m^2), this potential is corresponding to 30% (3.074 polygons covering 409.470 m^2) of all § 34 building polygons in the city. Both values use eaves height. Restricting the analysis to residential buildings, 52% of polygons exhibit a minimum height difference of 3 m. Again, selecting the lowest values for polygons linked to multiple street parcels, potential for 23% (2.317 polygons covering 250.314 m^2) of all § 34 residential building polygons can be found.

4. Discussion

Our study provides a comprehensive and grounded data-driven toolbox, that allows for assessing the regulative vertical extension potential of existing buildings in the city of Lüneburg, Lower Saxony, Germany, with the aim of supporting sustainable urban development. Hereby, a knowledge base for policy, planning, and administrative decision-making is provided. Given the aim of this study, we focus on the model and the two tools themselves and less on presented default output results.

4.1. *The overarching utility*

The tools serve as decision-support for urban planning to address development pressure, meet projected housing demands, and tackle land scarcity, thereby providing the data basis to reduce the environmental impacts associated with land take. Our model was originally conceived in response to the needs of its intended real world users, formulated through the transdisciplinary collaboration of the SUSTIL project. Its current use within municipal administration and political decision-making highlights the practical applicability. Throughout the design phase, the research team collaborated closely with various departments and actors of the Lüneburg city administration, incorporating feedback and iteratively shaping model and tool design. This resulted in a tool tailored to administrative workflows, data structures, and user needs as well as ensured a smooth tool transfer and (technical) integration. Municipal actors emphasised that the ability to independently generate, visualise, and interpret results without requiring external expertise was of particular value. This collaboration between the research team and real word users resulted in a balance between analytical depth and accessibility. In doing so, we aim to empower local actors. Local knowledge is incremental for creating place-based approaches [47,48]. However, many municipalities and administrative bodies face barriers regarding the implementation of data-driven information due to a lack of expertise or capacities [34], but rather rely on local knowledge of actors [49,50]. This may be feasible for smaller municipalities, yet such challenges become inherently more critical with increasing town or city size and heterogeneity [51], making quantitative assessments that support local knowledge more relevant [52]. Simultaneously, self-sufficient frameworks that empower and support local actors are relevant (e.g. [31,53]. Thus, approaches that make development potential tangible for planners and decision-makers are a crucial step toward more holistic urban planning processes [54,55]. This becomes especially important in the context of urban sustainability [56]. Even with limited quantitative dimensions, such efforts enable steering of sustainable development strategies, which contribute to promoting urban densification and reducing land consumption [50,57].

Through the integration of standardised base data and formats (development plans according to XPlan, ALKIS, LoD1), which are unified across Germany, the approach, even the toolboxes themselves, could be adapted to other German municipalities. While some regional calibration (e.g. setting floor height parameters, regulative thresholds, or typology-specific adjustments) may be necessary, such changes can be implemented without altering the core functionality of the toolbox. Hence, an application on a regional scale could be theoretically attempted, provided data is available. In the end, in Germany, planning and decision authority of vertical extension and more specifically handling of development plans as essential tool component lies with the

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[3] Due to the exclusion after the calculation process polygons may have been assigned to multiple street parcels. Therefore, the percentage may count polygons multiple times, similar to regular polygons.

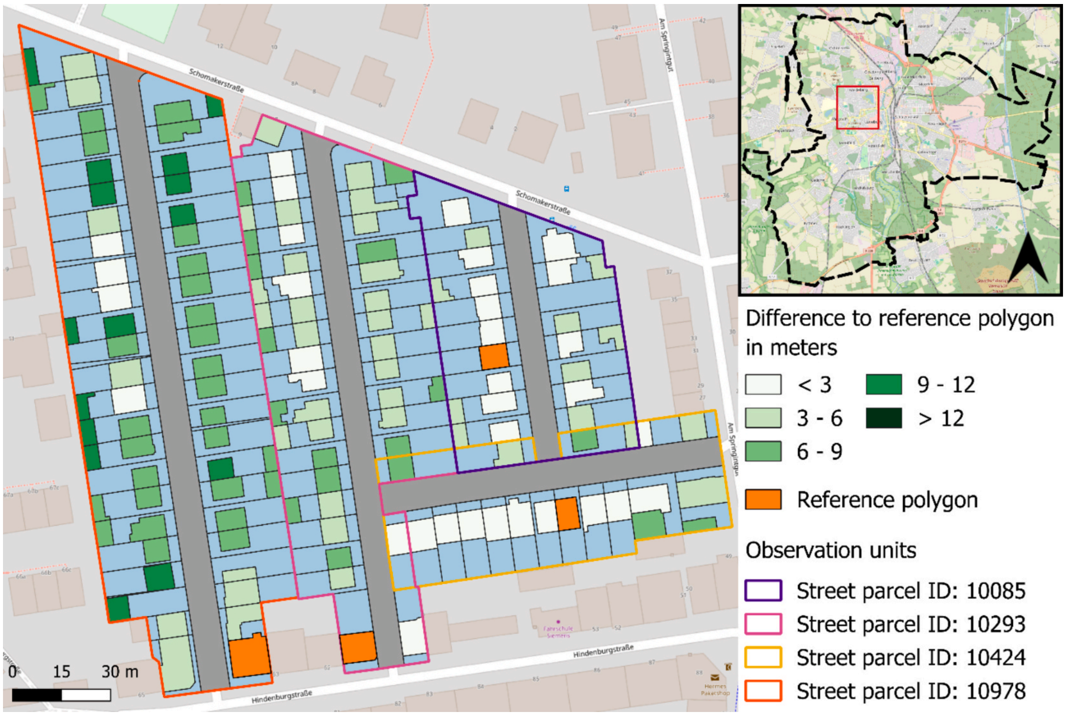

Fig. 5. Example (Kreideberg, Hanseatic city of Lüneburg, Lower Saxony, Germany) of calculated vertical extension potential for four street parcels using default tool settings (reference height is eaves height) (basemap © OpenStreetMap).

municipalities. Therefore, we still argue that the toolbox is best implemented at a municipal scale. Though we believe that the size of a municipality is of little relevance for transferability due to the utilised standardised input data in tandem with the tool accessibility, at least within Germany. Smaller municipalities with limited expertise may particularly benefit from the tool's simplicity and automation, thus overcoming their lack of capacities as well. Larger cities can integrate it into more complex analytical workflows or expand it with additional datasets. Internationally, other planning regulations apply, yet the core principle and approach remain relevant. This positions the toolbox as a scalable support instrument that can supplement broader efforts to operationalise sustainable urban transformations and land-use efficiency goals across diverse geographies.

We consider this transferability potential alongside the ease of use, flexibility, interpretability and calculation speed of the tools as key strengths. Even institutions with varying levels of expertise and capacities can carry out meaningful analyses with such tools and contribute to sustainable urban development decisions [58]. Generated insights into building location and typology enable subsequent advanced geospatial analyses of vertical extension potential [32]. Beyond practical use, through informed decision-making competencies alongside the understanding for sustainability transformation is enhanced [48].

4.2. Reflection of functionality

A major key challenge was to balance model complexity and accessibility. We believe that our toolbox provides highly informative and diverse output incorporating a variety of useful additional attributes (e. g. building use type and roof type) without overloading the user with complex input data and settings requirements. The model's state is the result of a transdisciplinary and iterative development process. This ensured continuous and flexible integration of practical knowledge, administrative requirements, and local planning needs. Such participatory approaches allow for capturing local needs, thus enhancing effectiveness for supporting integrated planning and sustainable development [59].

Both tools are designed so that only file paths need adjustment when new or updated data becomes available, provided no structural changes occur. The remaining development plans will be vectorised according to X-plan standards eventually by the city administration. Yet, unknown inconsistencies in parametrical structures may occur due to the diversity of plans. This originates in decades of plan iterations, as the first development plans of the German building code date back to the 1960 s. Such inconsistencies may cause issues with the tool scripts. Due to the well-established relationship between the research team and the city administration, we are optimistic to successfully incorporate them in the model eventually. Cities or municipalities potentially adopting our or a similar approach would need to advance their digitalization initiatives regarding development plans and other relevant planning data as well. As indirect effect, GIS projects such as ours can serve as incentives for long overdue general digitalization efforts in an administrative institution [60,61].

Building on this foundation, users are encouraged to supplement the output or expand the model with additional layers of data and information. For example, further contextual aspects such as urban density data, urban typology and structure types should be considered [62–64]. Moreover, identified potential may not be indicative of structural or architectural feasibility and other parameters such as fire security or visual character of the surrounding buildings. However, the inclusion of such factors would increase model complexity and required additional expertise regarding tool usability. It would then be up to the municipality or individual user to decide which additional parameters to incorporate into the analysis. In the end, as is the case concerning any model, simplification of certain complexities inherent in urban planning in favour of accessibility is necessary. Therefore, even though the model results suggest the potential for extension, they do not replace the need for detailed on-site assessments.

Another key aspect that balances usability with analytical scope concerns the treatment of floor levels. The tools apply a single floor level height across the city. This design decision is rooted in our goal of a holistic assessment, while maintaining simplism in favour of accessibility. Such generalization works well for most urban settings and is common practice among planners [65], though does not account for variations in architectural design (e.g. different periods of construction) or the specific characteristics of diverse buildings. This is especially prominent in historical towns and cities [66], of which Lüneburg is an example as its buildings originate from different building periods [42]. While most buildings in Lüneburg were built between 1949 and 1978 [42], supporting our approach, residential buildings for instance may require different floor heights across residential areas or compared to non-residential areas, leading to an over- or underestimation of the actual extension potential. Incorporating more building-specific data or finer-grained assumptions about floor-level heights would improve the model's accuracy. To tackle this challenge, we decided to include a parameter in both tools, where users can set the assumed floor level height themselves. The validation data further supports this decision, since most buildings are within a similar range, yet show some diversity in floor level heights.

Furthermore, a relevant limitation concerns the exclusion of roof geometry. While roof form strongly influences the structural feasibility of vertical extensions [31], the decision to omit this parameter in the analysis was made in favour of model consistency and complexity. This is especially relevant on the city scale. Including this factor would have increased model complexity and reduced adaptability for broader use. Since the model focuses on assessing potential within existing regulatory frameworks rather than engineering feasibility, this simplification aligns with the intended scope. Nevertheless, the inclusion of roof type information in the output ("DACHFORM" attribute) enables users to conduct their own differentiated analyses. For example, output could be filtered for only buildings with vertical extension potential and flat roofs.

In this context, a main limitation of our work is its focus on regulatory height allowances as the primary determinant of vertical extension potential. Other variables that may influence structural or economic feasibility, such as building age, material type, or maintenance status, were not included though relevant for actual vertical extension projects. This omission was intentional and rooted in the study's scope and aim in close collaboration with the city administration: to develop an accessible, transferable, and regulative grounded tool for initial screening of densification potential. Incorporating additional structural indicators would have increased model complexity and required data that are often unavailable or inconsistent across municipal datasets. While this limits the analytical depth and real-world application, it ensures usability and transferability. Future research should extend the model by integrating more variables such as detailed roof geometry and construction period or typology. This could serve as proxy for structural feasibility. While the model's precision for decision-making could be enhanced, increasing its complexity through adding more and complex data to incorporate additional factors will introduce similar issues for users, particularly regarding accessibility as well as obtaining suitable data.

Although the focus is primarily on residential development, we decided to include all building typologies and uses, providing a more holistic view of the city's vertical extension potential. This is particularly relevant for areas governed by § 34 BauGB, where non-residential buildings (such as industrial or commercial) can serve as height reference points for residential buildings. While the model not directly processes attributes like building type, and roof geometry, but focusses on height values, including these attributes in the output data enables advanced demand driven result assessments. However, the presence of non-relevant buildings, such as garages and smaller structures, may lead to an inflation of extension potential. Nevertheless, buildings non-relevant to the user can be excluded by setting the minimal area size in the tools as well as in filtering steps of the output data. This is a solution for users who, on the one hand, require a holistic approach to urban development and, on the other, prefer a streamlined analysis focused on residential buildings. Thus, users are provided with sufficient possibilities to independently carry out a nuanced analysis. Nevertheless, additional filter options, such as roof type, building typology or building use, directly implemented in the tool masks could benefit user-friendliness.

§ 34 BauGB of the German building code is specifically intended to allow for flexibility in assessing the suitability of vertical extension depending on local characteristics and needs. However, by employing qualitative criteria, especially in contrast to development plans, this results in high subjectivity and context dependency, thereby contradicting holistic as well as quantitative approaches. Even though our model aims to provide a starting point for determining potential, the inherent subjectivity makes it challenging to develop a consistent approach applicable on the city scale, but also across further urban contexts in Germany and beyond. This challenge is not new in the field of urban planning and land consumption (e.g. [67]. Amer et al., [31], who analysed vertical extension potential in the city of Brussels, Belgium, faced a similar challenge. For simplicity, they chose mean building height per street as allowable height in accordance with the urban regulations of the Brussels Capital Region.

Particularly, the reliance of our approach on street parcels and their given structure causes such barriers towards consistency. Due to their variance in extend ALKIS street parcels may lead to abstract output, contradicting real-world § 34 BauGB evaluation. This is indicated in the results, where street parcels show a high variance of associated buildings. Furthermore, as evidenced by the need for manual adjustments of street parcels in the pre-processing, the model's ability to provide fully automated results is hindered. On the other side, using street parcels as defining unit for the "surrounding area" allowed us to provide a tangible model approach for § 34 BauGB and utilise ALKIS, which is a well-established dataset among German Federal states. Thus, transferability and accessibility are ensured. Future work may explore different units of observation or additional approaches, e.g. considering reachability of urban green spaces [68] or walkability [64,69], to improve the model's practicality. Additional filtering options in the tool masks could further enhance the user-experience and improve the output assessment more tangibility, particularly for non-experts.

4.3. What can results mean?

Our default model results reveal that depending on the evaluation approach up to 63% of building polygons within § 34 areas exhibit a potential of at least one floor level, providing promising opportunities for densification within these areas. Utilising the provided attributes of the output and applying various filters, such as further specification of polygon areas or building function, enables a much more refined and nuanced assessment of potential steered by user demands. For § 34 BauGB areas building polygons may correspond to multiple units of observation. Herewith it is possible to address different types of assessments, for instance, a conservative approach can be adopted by considering only the lowest value for each polygon linked to multiple street parcels and focussing on residential building only. This leads to a more grounded assumption of 23%. Alternatively, using mean or maximum values could also be viable options. In contrast, while only a fifth of development plans are currently available, the analysis uncovers a certain trend. Buildings within those areas only show marginal potential of just 3%. From a planning and decision-making perspective, the identified lack of potential suggests two possible approaches: either to focus on horizontal extensions and infill development to address housing demand or to revise existing development plans to permit greater building heights. Here, the "Bau-Turbo" may serve as a suitable regulatory instrument, building on these insights to facilitate targeted adjustments. The results help reveal where existing regulations constrain inner development and, consequently, where and to what extent policy tools like the new "Bau-Turbo" may be necessary to unlock additional potential. However, it remains to be seen whether the remaining development plans will exhibit higher potential once incorporated into the analysis. In sum, one can argue in favour of substantial potential for vertical extension within the city, which could contribute to meet the projected demand of 3.490 additional residential units until 2040 [41].

This insight aligns with the results of Amer et al. [31] and [32], who as well identified significant opportunities for additional urban housing in their respective study areas. However, our results were produced with default settings and are subject to change depending on tool settings, applied subsequent filtering and evaluation approaches by users. Therefore, users are encouraged to choose own settings and assess the output independently, according to their needs, posed questions and perspectives.

Lastly, the results can be visualised directly on the map canvas, enabling users to identify and locate specific buildings with extension potential. This not only helps estimate the quantity of overall capacity but also highlights where within the study area such potential exists.

4.4. Implications

Beyond individual cases, the results produced by the tools carry significant implications for urban planning and development strategies in the greater scheme of things. The tools provide grounded guidance for decision-making, depending on whether potential is uncovered and, if so, to what extent. In scenarios where potential is limited within the city, planners and politicians face a difficult challenge: determining how to accommodate urban development without compromising sustainability objectives.

In areas where potential is present, the tool outputs highlight opportunities for vertical extension to steer development more strategically. These areas could benefit from new guiding principles or innovative zoning regulations to encourage sustainable urban growth and transformations. For instance, mixed-use buildings offer a sustainable way to optimise land use while enhancing urban vitality (e.g. [70,71]. In cases where potential is identified further local assessments should be carried out to reliably verify the existence and degree of potential. Further aspects, such as structural feasibility, clearance areas, fire protection, infrastructure facilities and accessibility, should be evaluated to determine potential [3,31]. It needs to be emphasised that the model serves as a theoretical planning instrument aimed at improving the underlying data for (political) decision-making and steering urban development. The actual realization of building extensions ultimately lies in the hands of property owners, where the various other factors, such as those already mentioned, need to be considered. Within the scope of this study in tandem with data privacy, we did not tackle building ownership. However, this factor is of relevance and should be included in expanded tools or in future research, if data access allows. Yet the tool shown here allows for planning at a larger e.g. municipal scale. This, on the other hand, represents a fundamental limitation for planning authorities, as the translation of potential into action depends on individual willingness, public acceptance, financial capacity, and further regulative aspects. Supporting frameworks and incentives for densification initiatives may be needed to bridge this implementation gap [72,73]. Our findings thus serve as an evidence base for identifying where such incentives or simplified procedures would have the greatest impact. The toolbox does not directly trigger physical construction but supports the creation of enabling conditions, for example, by helping municipalities prioritise areas for targeted funding schemes, subsidies, pilot projects, or streamlined approval under regulatory instruments (e.g. [74]. This way, the model bridges the gap between spatial analysis and policy implementation, translating data into actionable urban planning intelligence. Here, the recently enacted Bau-Turbo (§246e BauGB) and the related amendments to §§31 (3) and 34(3b) BauGB introduce flexibility for municipalities to deviate from existing development plans and permit additional residential construction, including vertical extensions, without undergoing lengthy amendment procedures. These new instruments are a step in the right direction and expand the range of planning options but do not override existing regulations. Instead, they complement established planning law by enabling faster implementation, especially where potential has already been identified. We argue that our toolbox directly supports this process by providing a spatial evidence base to locate and quantify such potential areas. Thus, the “Bau-Turbo” framework increases the practical value of the toolbox, helping municipalities to identify where regulatory flexibility can be most effectively applied for sustainable densification. It remains to be seen if this incentive is a sufficient answer to the overall challenge of promoting inner urban development at scale, given the multitude of other limiting factors for vertical extension, including individual willingness, financial feasibility, and social acceptance. Without complementary measures, such as financial support programs, awareness campaigns, and local planning capacity building, the regulatory simplification introduced by the “Bau-Turbo” may have limited practical effect. Nevertheless, such frameworks demonstrate political willingness, thus underscoring the relevance of tools, models and analysis such as ours that unlock potential on the other hand.

Within these challenges, utilising our toolbox to explore vertical extension potential can act as catalyst to facilitate space-saving innovative solutions and promote urban sustainability transformation on both neighbourhood and building level. This includes compact residential typologies in integrated locations [41], mixed-use, blue-green infrastructure, urban food production or adaptive reuse of underutilised buildings (e.g. [75–77] as well as more holistic concepts, such as new urbanism (e.g. [78,79]) and smart growth (e.g. [80,81]).

In summary, the following key contributions are achieved by our approach: First, a comprehensive mapping of vertical expansion opportunities across the city of Lüneburg is provided. By integrating planning law and standardised geospatial data, it offers a thorough analysis of urban space utilisation. Second, the model utilises a regulatory informed and flexible approach, including areas with detailed development plans and those governed by § 34 BauGB. Through the inclusion of additional attributes, such as building use, the model’s practicality is enhanced. Third, the model provides a powerful toolbox for the city administration to make independent data-driven decisions, thereby pushing digitisation efforts. It offers fast, city-wide quantitative approximations of where vertical extension is (in-)feasible, driving targeted urban development and supporting sustainable development strategies. In this sense, the toolbox serves as a diagnostic instrument to inform future planning strategies and policy interventions, rather than as a prescriptive tool for direct implementation. Fourth, as cities continue to face housing challenges in tandem with land saving targets, this model can and should be expanded to incorporate additional factors such as economic feasibility, land-use zoning, or structural assessments, providing a broader framework for future urban planning efforts.

5. Conclusion

The model and its tools provide more than just an assessment of vertical expansion potential. They serve as a first step decision-support system that enables planners to rethink and modernise urban development practices and even tap into new planning concepts. Whether the results reveal opportunities or constraints, the tools empower actors to develop data-driven strategies that align with sustainability objectives, balance housing demands, and foster innovative approaches in urban planning. Further research and model refinement, particularly in the context of § 34 BauGB areas, data updates and additional factors, will enhance the model’s applicability and accuracy. The tools do not replace detailed on-site evaluations. Rather they offer a pathway to guide discussions on adapting current regulations, embracing new building typologies, and advancing sustainable urban development in an ever-changing landscape.

CRediT authorship contribution statement

Christoph Schwenck: Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Formal analysis, Conceptualization. **Tobias Neumann:** Writing – review & editing, Project administration, Methodology, Conceptualization. **Henrik von**

Wehrden: .

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cacint.2026.100382.

Data availability

The toolbox and certain input data are not publicly available due to municipal ownership and restrictions. Output result data are provided as supplementary material.

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