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GIS-based Identification of Densification Types

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1 ABSTRACT

Due to the prevailing settlement pressure and the increasing demand for living space, land consumption is draining the limited land reserves in the alpine region. From 2018 to 2020, an average of 11.5 hectares of land per day were used in Austria[1]. Until 2020, while the population grew by just 10.9 percent, land use in Austria has increased by more than 27 percent since the turn of the millennium[2]. As urban sprawl increases, green spaces decrease and are more and more sealed by asphalt and concrete. To avoid the constant exploitation of open and green spaces, promoting higher land-use efficiency by densification within existing settlement areas is pursued as an alternative, more sustainable path of settlement development. It is therefore essential to provide decision-makers, planners, developers, and architects with a detailed overview of the densification potential within current settlement areas. This paper introduces a GIS-supported methodology to facilitate this task.

In our research within the Alpine Building Centre – Simulation of Settlement Systems (Zentrum Alpines Bauen), we first developed a GIS-analysis model for the automated identification of theoretical densification potentials on building plot level while taking legal building regulations and local specifications for structural density into account. In a further step, we elaborated a building-related typology for the classification of these potentials, by integrating the geometry and cubature information of the existing building stock and building plots. GIS analysis models were then developed in accordance with this typology to identify and quantify these potentials theoretically, and to model their generalized three-dimensional (3D) shapes. The proposed typology characterises current densification potentials in Salzburg state into four types: building replacement, roof stacking, building extensions, and independent building annexes. As a case study, this analysis was implemented on a test municipality in Salzburg state - Henndorf am Wallersee. Experimental outcomes are visualized in an interactive 3D web map that provides an overview of the result. The outcome data provide important information and a planning basis that support local planners and decision-makers in achieving more sustainable, resource-efficient future settlement development.

Keywords: GIS-analysis, densification potential, densification typology, 3D-web map

2 INTRODUCTION

The Alpine region is confronted with major planning challenge: While the availability of land is severely limited by natural landscape conditions, the demand of living space increases and thus results in high settlement pressure. Under this pressure, built-up urban areas expand with inefficient land use and leads to urban sprawl, which is a crucial issue for sustainable development in the future (EEA, 2006). It inevitably causes a loss of agriculture land and open green spaces, and in return a replacement with almost irreversible sealed soil. Such unsustainable use of land has negative impacts on the quality of life and ecosystems, which includes aspects such as agriculture production, biodiversity, climate protection, energy consumption, increased mobility, etc. (EEA, 2019). These negative effects can bring about potentially serious environment, economic, social and health risks. Until 2020, while the population grew by just 10.9 percent, land use in Austria has increased by more than 27 percent since the turn of the millennium (WWF, 2021). Accordingly, Austria has set a national-wide soil protection strategy for more economical land use with a target for

[1]Flächeninanspruchnahme. (2021, June). Umweltbundesamt. https://www.umweltbundesamt.at/umweltthemen/boden/flaecheninanspruchnahme

[2] WWF: Bodenverbrauch fast dreimal so stark gestiegen wie Bevölkerungswachstum. (2021, December). WWF. https://www.wwf.at/wwf-bodenverbrauch-fast-dreimal-so-stark-gestiegen-wie-bevoelkerungswachstum/

reducing land use to a net of 2.5 hectare per day by the year 2030 (Bundeskanzleramt Österreich, 2020). However, the average consumption of land in Austria from 2018 to 2020 amounts up to 11.5 hectares per day (Umweltbundesamt, 2021), which significantly exceeds the target.

Such excessive land use is not a unique phenomenon in the Alpine region. It is one of the major environment challenges in Europe (EEA, 2006). To address this problem, 'No Net Land Take' in EU by 2050 is promoted in the 7th EAP (EU Environment Action Programme to 2020) and the EU Roadmap to Resource Efficient Europe (European Commission, 2011). This 'No Net Land Take' goal aims to reduce the effect of urban sprawl by avoiding sealing agricultural land and open spaces. Instead, it stresses the focus to the utilization of land that has already been sealed (Science Communication Unit, 2016). In response, densification (or infill development) is promoted by policymakers and pursued as a solution to urban sprawl (Artmann, Inostroza, & Fan, 2019). Priority is stressed for inward settlement development in the spatial planning handbook for Salzburg state (Amt der Salzburger Landesregierung, 2012). By concentrating development in existing settlement areas, additional dispersed, low density settlement development is prevented. As result, land that may consumed by urban sprawl is spared. Reasonable densification is considered as a crucial element to the path of sustainable development (Marique & Reiter, 2014; McConnell & Wiley, 2012; Pelczynski & Tomkowicz, 2019; Wicki & Kaufmann, 2022).

Several case studies in European countries that provide overviews and recommendations for densification are conducted: Nabielek (2011) summarized the Dutch national urban planning policy concerning densification, and ,through empirical research, provided insights of the intensity and types of locations of densification within the existing urban area in the four largest Dutch cities; Attia (2015) first reviewed the existing building stock in Liège city, Belgium, then he generalized urban densification scenarios of the city along with recommendations and potential challenges; Netsch (2021) gave an overview of 22 densification projects in Salzburg over the past 25 years. With the advance in open data availability, geospatial data have been used to the automatic identification of densification potential in multiple scales: Vuckovic et al. (2017) proposed a computational environment to generate potential densification schemes in 3D based on a spatial dataset in an urban area within the city, Graz, Austria; Abedini and Khalili (2019) used multi-criteria evaluation techniques combined with geographic information system (GIS) to determine the capacity of Urmia, Iran, and identified suitable plots for densification; Eggimann et al. (2021) presented a geospatial simulation framework to evaluate densification potentials at neighbourhood level; Amer, Reiter, and Attia (2018) adopted multiple criteria and boundary conditions to identify densification potential through roof stacking; Schiller et al. (2021) validated the feasibility of automated detection and monitoring of densification potentials via GIS-based procedures.

As it is mentioned in the guidelines for the 'spatial development concept' of Salzburg state, densification potentials are considered as one essential source of building land reserves (Land Salzburg, 2019). It is therefore important to provide a detailed overview of these densification potentials. This paper introduces a generic GIS-supported methodology for the automated identification of theoretical densification potential types on building plot level. Our objective is to assess and quantify the densification potentials that exist in the current settlement areas for each densification type. Using available geospatial data, we model the theoretical generalized 3D shapes of these potentials and provide a realistic view of them in an interactive web map. With this tool, we aim to assist decision-makers, planners, developers, and architects in recognizing and reflecting on the existing densification options. The delivered information can serve as a basis for further investigation for on-site implementation.

3 APPROACH

3.1 Densification types

Urban densification within existing settlement areas can be implemented through building extension in both vertical and horizontal directions (Attia, 2015). In our research, four densification types are further derived based on their characteristics among these two general densification directions. The first type is building replacement - replacing existing low-density buildings with new residential building structures with higher density. The second type is roof stacking. With this densification type, buildings are extended vertically - additional stories are added to the top of existing buildings in order to accommodate more households, thus occupying more land are avoided (Amer, Mustafa, Teller, Attia, & Reiter, 2017). With both the third type, building extensions, and the fourth type, independent building annexes, the horizontal extent of existing buildings are expanded. For example, building potentials located in the gardens of built-up building plots are utilized for constructing new residential buildings (Marique & Reiter, 2014). The difference between these two types is that, with the type „building extension", an extension is directly attached to existing building, while independent building annexes are additional residential units that share the same building plots with existing buildings but are unconnected to the existing buildings and are usable independently. The building-related typology that we established for the classification and GIS-based identification of densification potentials are based on these four types.

It is worth noting that, besides above-mentioned densification types, gap closure is another type of urban densification that are adapted in the cities (Attenberger, 2014). It is to fill the gaps between existing buildings on neighbouring building plots with new dwellings (Amer et al., 2017). However, this type is excluded from this research, as the filled gaps are across building plot boundaries which are not depictable in our building plot-based analysis.

3.2 Simulation parameters

The future development of settlement area regarding densification is constrained by various spatially relevant conditions that are listed in land development law and building regulations. There are horizontal and vertical limitations of spatial growth when it comes to expanding existing building stocks for additional living spaces (Vuckovic et al., 2017). Spatial relevant parameters are used as constraints in this study for the establishment of the building-related typology for densification potentials and the simulation of possible cubature for densification at each building plot. These parameters include legal building regulations for Salzburg state and local specifications for structural density.

According to the land development law of the Salzburg state (Land Salzburg, 2015), the buildings must be located in the building plot in such a way that their fronts are at least from the boundaries of the building site by a minimum distance of 3/4 of their eave heights, but in any case larger than 4 meters. Therefore, in this research, we use this constraint as a baseline to model the maximum possible height of each simulated cubature.

Moreover, since the municipalities in Salzburg state (except for Salzburg city) usually do not have digital development plans, from which the maximum building density can be automatically read out by GIS analysis models, the concept of local specification for structural density (*Ortsübliche Dichte*) is introduced in this research (Gadocha, Spitzer, Deng, & Prinz, 2021). For each analysis building plot, its structural density is calculated from an intersection with the available spatial dataset of building stock in Salzburg state. The second highest density for each analysis plot is derived from the surrounding eight analysis plots and stored as the local specification for structural density for this building plot. The local specification for structural density includes following parameters: ground space index, floor space ratio, cubic index, number of full floors, and ridge height. Table 1 provides an overview of these parameters and their definitions.

Parameter Name	Definition
Ground space index	The ratio between the building's footprint area and the surface area of the corresponding building plot
Floor space index	The ratio between the permissible aggregate surface area of all the storeys in a building and the surface area of the corresponding building lot
Cubic index	The ratio between the cubic meters of building mass and the surface area of the corresponding building lot
Number of full floors	The number of all floors of a building except basement, roof, and attic floors
Ridge height	Height of a building measured up to the ridge

Table 1: List of parameters used for local specification for structural density.

3.3 Building-related typology for densification potentials

To automatically identify and quantify densification potentials regarding previously introduced densification types with GIS analysis model, a building-related typology (Fig. 1) was established with taking legal building regulations and local specifications for structural density into account. Values of the modelling parameters used in the typology were chosen in consultation with urban planners from spatial planning

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departments of the city and state as well as stakeholders from a non-profit housing association. However, these values can be adjusted accordingly to fit individual study areas and particular development regulations.

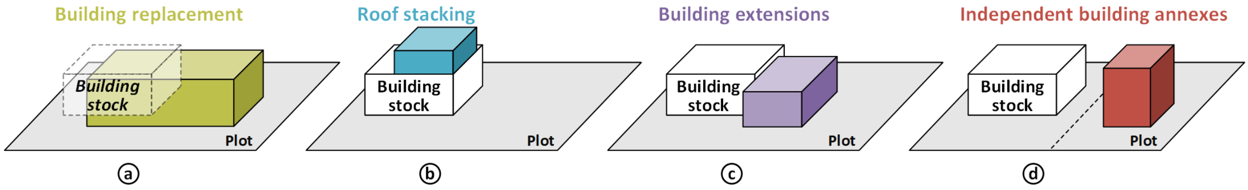

Fig. 1: Illustration of the building-related typology: (a) Type 0: Building replacement, (b) Type 1: Roof stacking, (c) Type 2: Building extensions, (d) Type 3: Independent building annexes

Type 0: Building replacement

For this type, under the consideration of the legal distance requirement (minimum distance equals to 4 meters or 3/4 of the eaves height), possible cubatures are simulated for each analysis building plot. The maximum utilization of each analysis building plot is then selected according to the calculation of gross floor area of each simulated building model. The selection of the maximum utilization is limited by the condition that the simulated cubature doesn't exceed any local specification for structural density.

Type 1: Roof stacking

For this type, the simulation of possible cubature is limited to the extent of the footprint of building stock. Existing buildings with minimum 90m² gross floor area are selected for the simulation. Under the consideration of the legal distance requirement and local specification for structural density, simulated roof stacking model with the largest gross floor area is selected. Simulated roof stacking model is the part of the simulated cubature that is above the ridge height derived from the existing building. The total cubature of existing building and roof stacking model is limited by local specification for structural density. Additionally, the roof stacking model should be wider than 5 meters and with minimum 85 m² gross floor area (approximately 1 housing unit).

Type 2: Building extensions

For this type, the extent of the simulated cubature's footprint is limited to the rest of its located building plot minus the existing building's footprint. Following the legal distance requirement and local specification for structural density, a simulated building extension that is directly connected to the existing building and with the largest possible gross floor area (larger than 85 m², approx. 1 household) is selected. The minimum width of the building extension models is differentiated into potential for the extension of living space (width from 5 to 8 meters) and potential for additional residential units (wider than 8 meters).

Type 3: Independent building annexes

In the simulation of independent building annexes, as in the case of building extensions, the footprint of the simulated cubature is restricted from overlapping with the existing building's footprint. However, the annex model is required to have a minimum distance to the neighbouring existing building. Two variations are modelled in this research. The first variation is to add building annexes without building plot division. In this variation, a minimum distance of 3/4 of the height of the existing building plus 3/4 of the height of the annex model between them is assumed. The second variation is that when a building plot is suitable for subdivision based on its shape and size (larger than 1200 m²), selection criteria of a minimum distance of 15 meters between the existing building and the annex model, as well as a minimum gross floor area of 180 m² of the annex model is assumed.

3.4 Workflow

The methodology (Fig. 2) for deriving densification types starts with the selection of building plots depending on land use zoning. For these plots, different cubatures are simulated depending on distance to the parcel boundaries in the simulation model. For each cubature, its density parameters (i.e., ground space index, floor space ratio, cubic index, number of full floors, ridge height) are calculated. For each plot, the structural density is estimated by the eight nearest neighbouring existing buildings and their plots. Depending on the derived structural density as a constraint, the cubature with the maximum gross floor area is selected.

The difference of this maximum gross floor area and the gross floor area of the building is assumed as the densification potential of type 0 (Building replacement).

In the next step, the plots with a densification potential of type 0 are simulated again for the other types in a similar way but with different parameters and constraints (according to the typology, see section 3.3). For type 1 (Roof stacking) the footprint of the building stock is used, for type 2 (Building extension) and 3 (Independent building annexes) the plot minus the existing building's footprint is used. The selected cubature of type 2 has to be connected to the existing building and for type 3 the selected cubature must be detached from the existing building with a defined minimum distance.

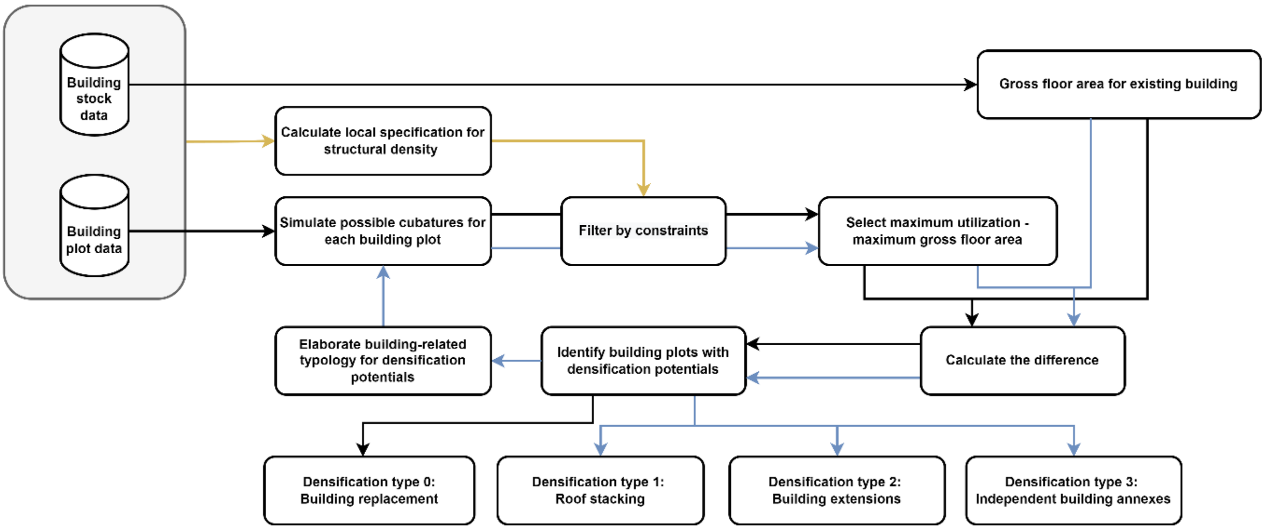

Fig. 2: Workflow of the GIS-based identification of densification types

4 CASE STUDY AND RESULT VISUALIZATION

Henndorf am Wallersee is a municipality located in the north of Salzburg state. It is with an area of 23,51 km² and 4933 inhabitants by 2020 (Salzburg Wiki, 2022). This section focuses on a case study of this municipality. Previously introduced densification type identification workflow was implemented in this test municipality. As outcome, densification potentials in accordance with the building-related densification typology are identified and quantified for each land parcel. An overview of the analysis result is given in this section (see Table 2). Additionally, in this section, we introduce the prototypical user interface and features of the interactive web map that was developed for the visualization of the analysis result in 3D (see Fig. 3).

4.1 Experimental results

In our case study, residential building plots that are built-up with buildings' footprints larger than 12 m² and with construction windows larger than 100 m² or wider than 10 meters are selected for the analysis. There are 3625 building plots in Henndorf, with 40% designated for residential building plots. Among these building plots, almost 51% of them, which takes up more than 78% of the total area, are already built-up with buildings that meet our selection criteria. According to our experimental result (see Table 2), almost half of these analysis building plots are identified with densification potential (or underused). It means that the gross floor area of the existing buildings on these building plots are smaller than the theoretical maximum gross floor area that can be achieved. With the densification type 0 – building replacement, approximately 1144 housing units could be added. Among the other three densification types, most building plots with densification potentials are identified with the possibility to add building extensions (i.e. Densification type 2), corresponding to accommodation of approximately 857 households. More than 95% of these building plots have the potential to add an extension that is wider than 8 meters, which can be used to create new residential units. It is possible for around 25% of the underused building plots to add independent building annexes to the existing buildings. Only less than 3% of the underused building plots are eligible for building independent annexes with land subdivision, which could add approximately 92 housing units. As for the densification type roof stacking, limited by the cubatures of the existing buildings, only around 4% of

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the underused building plots have such potential. Approximately 18 housing units can be created by this densification type.

Henndorf am Wallersee		Building plots		Potential [Maximum utilization, Local specification for structural density, Densification types]	
		Number	Area	Gross floor area (m²)	Housing units (85m² per Housing Unit)
Building plots		3625	2352.6 ha	-	-
Residential building plots		1468	93.8 ha	-	-
Built-up building plots - Buildings ≥12m² - with construction windows (≥100m² / ≥10m)		745	73.7 ha	-	-
without potential		*388*	*33.9 ha*	*6483*	*0*
Type 0 Building Replacement		**357**	**39.8 ha**	**111131**	**1144**
Type 1 Roof Stacking		**16**	**2.2 ha**	**1993**	**18**
Type 2 Building Extensions	**Living space extension**	**277**	**32.7 ha**	**83805**	**857**
	Additional residential units	**265**	**31.2 ha**	**80731**	**827**
Type 3 Independent Annexes	**Without subdivision**	**91**	**15.1 ha**	**32930**	**344**
	With subdivision	**10**	**3.6 ha**	**8226**	**92**

Table 2: Summary of the identified densification potentials in Henndorf am Wallersee

4.2 Web visualization

In order to make the analysis result easily accessible and explorable for our target groups (i.e. decision-making authorities, planners, developers, and architects), an easy-to-use, straightforward 3D web map is developed to facilitate this task. Figure 3 provides an overview of the application's user interface and its components. The components of the user interface can be divided into following categories: application header, 3D map elements, and core features that allow users to interact with the identified densification potentials regarding each densification type.

The header (Fig. 3 – A) includes the title of the application, followed by a short description of the application's purpose. 3D map elements include a main map view (Fig. 3 – B1), map controls (Fig. 3 – B2), layer list (Fig. 3 – B3), address search panel (Fig. 3 – B4) and pop-up window (Fig. 3 – B5). The map view provides a 3D view of selected study region, with OpenStreetMap and world hill shade layer from ArcGIS Platform as base map. Map controls include zoom control, navigation toggle for panning or rotating the view, home button and compass button for resetting the map extent and orientation to default, full-screen control, and base map gallery widget for switching map view's base map. The layer list at bottom left corner indicates the visualized map layers. Users can control the visibility of individual map layer with the 'eye-shaped' toggle in each layer panel. Map legend is integrated into the layer list. Core features include densification type selection cards (Fig. 3 – C1), summary panel (Fig. 3 – C2), feature table (Fig. 3 – C3), distance and area measurement toggle (Fig. 3 – C4), as well as daylight and shadow simulation widget (Fig. 3 – C5). Each selection card represents one densification type, followed by a brief description of each type. With one densification type selected, generalized 3D geometries of the corresponding type of identified densification potential are visualized in the map view. Densification type roof stacking is selected and shown in Figure 3. The visualization results of the densification type building extensions and independent building annexes are shown in Figure 4. In the summary panel, extra living area (gross floor area) and household capacity that can be theoretically created by the selected type of densification are summarized. With the interactive feature table, users are provided with a tabular view of each visualized geometry's attributes. Multiple interactions are supported by the feature table: Features can be sorted by attributes in ascending or descending order; Users can select feature of interest from the table, highlight and zoom to the selected feature in the map view. By clicking on the filter icon at the right top corner of the summary panel, a filter list is expanded. It allows users to filter and visualize a subset of the identified densification potentials that satisfy the user-defined criteria based on their feature attributes (Building volume, height, number of full floors). Users can set filter thresholds by dragging label thumbs or editing their label values above (Fig. 3 –

C2.1). The filtered results are highlighted in the map view (Fig. 3 – C2.2). Contents of the summary panel and the feature table are updated automatically when a filter is applied to the dataset. Users can remove all filters by clicking on the reset button.

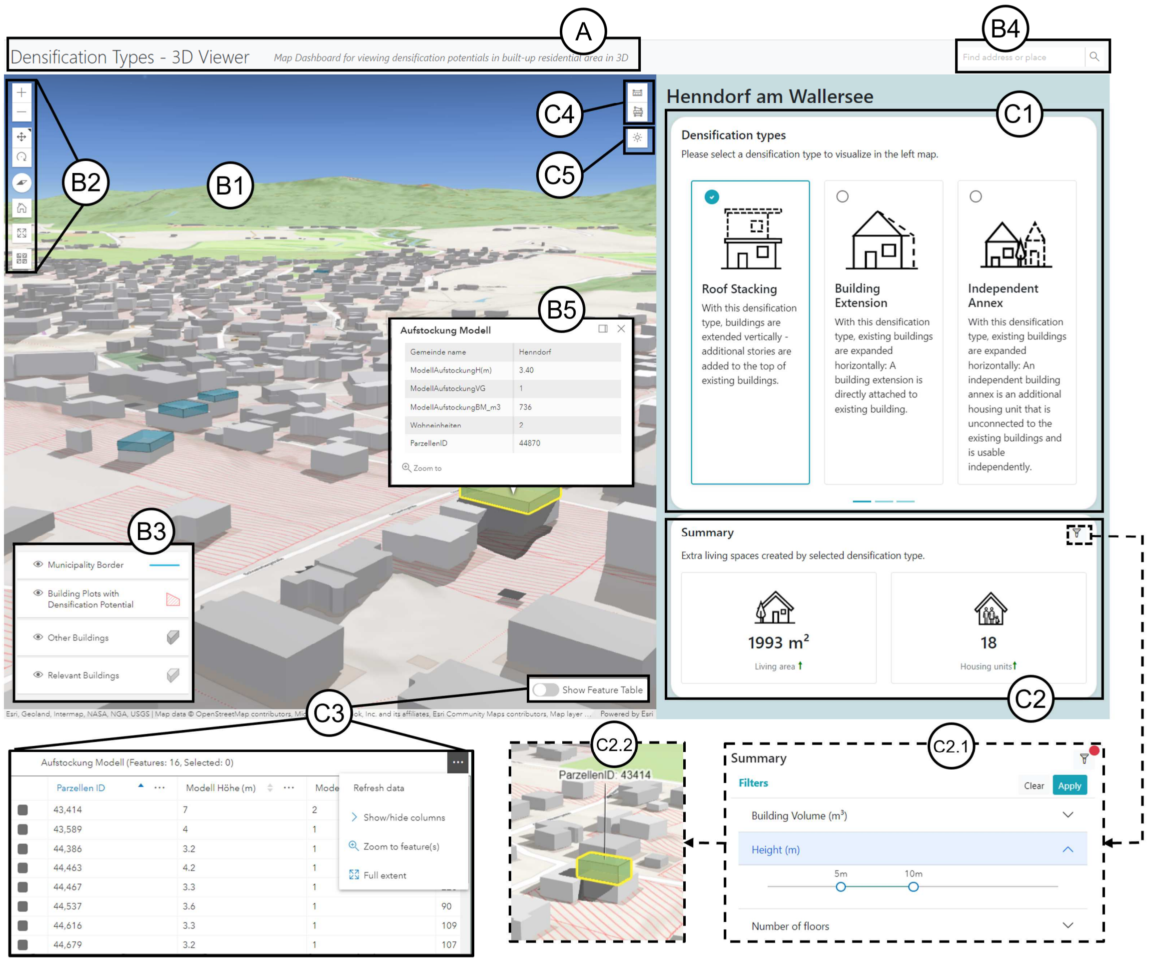

Fig. 3: User Interface: Use case in Henndorf am Wallersee. Densification type 'roof stacking' is selected. (A) header, (B1) map view, (B2) map controls, (B3) layer list, (B4) address search panel, (B5) pop-up window, (C1) densification type selection cards, (C2) summary panel, (C2.1) expanded filter with user-defined height threshold, (C2.2) simulated roof stacking model selected by filter (C3) feature table, (C4) measurement toggle, (C5) daylight and shadow simulation widget.

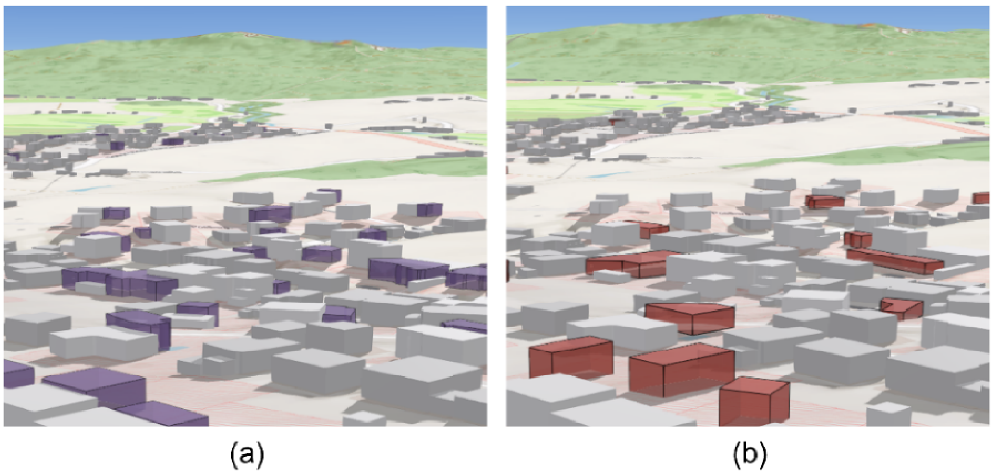

Fig. 4: Visualization of the identified densification potential: (a) building extensions, (b) independent building annexes.

The implementation (Fig. 5) of this interactive web map is mainly on client-side. Data to be visualized in the web map are initially stored in a file geodatabase. These data are then imported via data management tools in ArcGIS Online and published as ArcGIS data service. They are hosted in the cloud as feature layers in a

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feature service (ArcGIS Developers, 2022b). The user interface (client-side) of the web map is implemented using HTML, CSS, and JavaScript. The design of the user interface is supported by additional libraries including Bootstrap and Bootstrap Icons. The user interactivity of the web map is enhanced by JavaScript and JavaScript library jQuery. To allow client side to access the data from the hosted feature layer, we use ArcGIS API for JavaScript (ArcGIS Developers, 2022a), a web API provided by ArcGIS. It allows us to display, query and filter data in our map application. To visualize the densification potential geometries in 3D, we embedded a local scene in our map view. It allows us to project our data on a plane in a 3D environment. Existing buildings and the identified densification potential geometries are the visualized 3D features in this scene. Their footprints are displayed on the terrain and extruded based on derived height information. These features are placed in the scene based on their located building plots' average absolute heights to the sea-level.

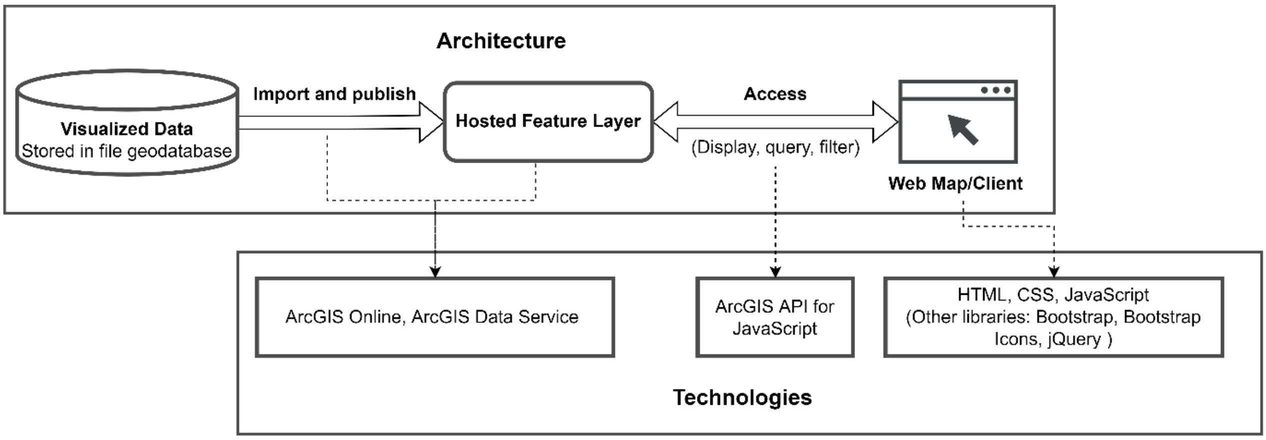

Fig. 5: Implementation of the web map

5 CONCLUSION

This paper introduces a generic GIS-supported methodology for the automated identification of theoretical densification potential types on building plot level. In this paper, we first characterised current densification types in Salzburg state. Then we introduced the spatial relevant parameters used as constraints for the establishment of the building-related typology for densification potentials. These constraints include legal building regulations and local specifications for structural density. Based on these constraints and combined with the characterised densification types, we proposed a building-related typology for densification potentials within existing settlement areas. It includes four types: building replacement, roof stacking, building extensions and independent building annexes. Later, we described the geospatial data-driven workflow used for identifying built-up building plots with densification potentials and modelling theoretical generalized 3D shapes of these potentials per the previous proposed building-related typology. This workflow was then implemented on a test municipality, Henndorf am Wallersee. The result shows that nearly half of the selected analysis building plots are underused and have great potential for densification: with the type „building replacement", over a thousand new housing units could be created; Limited by the size and shape of the existing buildings and building plots, the type „building extensions" can add over 800 housing units, while the type „independent building annexes" can add around 90 housing units and the type „roof stacking" with the creation of only 18 housing units. Furthermore, to visualize the analysis result in a realistic scene, a straight-forward, interactive 3D web map was developed. We introduced the user interface, features and the implementation of this web application in this paper.

It should be noted that this methodology is not meant to substitute building-by-building investigation for the implementation of densification. The analysis results of the creatable housing units and the generalized 3D shapes with different densification types do not represent the real future development. It represents the maximal potentials that are derived from our simulation based on the available geospatial data and parameters assigned to the constraints used in our GIS model (see section 3.2). In reality, the implementation of such densification process is rather complex, which is affected by multiple factors such as availability of the building plots, opinions of the house owners or neighbours, as well as materials and accessibility of the existing buildings, etc. However, the quantified results of this methodology can serve as an information basis in the planning phase: for example, during the expert consultation provided to building owners in the research project „BONUS" (Schöpflin, Erber, Madlener, & Prinz, 2022).

The focus of this study is to provide a generic methodology that can use spatial dataset to identify densification potentials within existing settlement areas in terms of location, generalized building shapes and creatable housing units per densification types. It aims to make such information accessible for decision-makers, planners, developers, and architects, thus assisting them in recognizing and reflecting on the existing densification options. The delivered spatial information of the identified underused building plots can be used for the creation of the densification potentials inventory in the context of land-use management. It provides relevant data to steer densification process from building plot scale. This methodology can be applied to other municipalities in Salzburg state. It helps decision makers and planners to follow the guideline for the spatial development concept (Land Salzburg, 2019) and to formulate spatial development concepts for individual municipalities in Salzburg state, with the aim of promoting inward settlement development so as to achieve more sustainable, resource-efficient settlement development in the future.

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