Geospatial simulation of urban neighbourhood densification potentials

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1. Introduction

Densification (also urban consolidation or redensification) has been put forward as an urbanization strategy for the efficient use of limited space for living, to intensify the built form and to realise compact cities as opposed to sprawling cities (Jenks & Burgess, 2000; Jenks, Burton, & Williams, 1996). Building sustainable cities, as outlined in the Sustainable Development Goals (United Nations, 2019), necessitates sustainable urbanization which reduces per capita environmental impacts of living in cities. However, as a result of urban sprawl, the percentage of very low-density areas is increasing in most OECD countries and is leading to environmental problems such as increased air pollution and greenhouse gas emissions (OECD, 2018). The predominant pattern is that urban areas are expanding fast and green areas are vanishing fast in many cities around the globe (Gerten, Fina, & Rusche, 2019; Richards & Belcher, 2019). In most European countries, rather than densification, land take is by far still the dominant land management strategy (European Environment Agency, 2018).

As a first response to the call for increased densification, undeveloped existing building zones in urban areas have been the first focus of analysis. In many places, this was accompanied by urban transformation efforts considering the conversion of industrial wastelands or brownfield areas to residential neighbourhoods by the replacement with new buildings (also known as grey recycling). However, the availability of undeveloped building zones or suitable former industrial sites is limited and in many cases becoming scarce. But not all densification is the same. As a starting point of our analysis, we build on at least three findings from literature (cf. Section 2): We assume that densification is more sustainable in central and well-connected locations. Also, we focus on neighbourhoods, which opens up additional opportunities for urban transformation going beyond the adaptation of the individual building. In addition to that, we focus on neighbourhoods from the post-war period whose renewal and densification yields high sustainability benefits from an energy point of view. We argue that our focus of analysis...
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considering neighbourhoods, geographic location and building age allows for more realistic densification potentials estimation and we hypothesize, that there is considerable potential for densification in post-war neighbourhoods. We test this hypothesis at a national scale for Switzerland and include further constraining factors that limit the practicability of densification projects when assessing densification potentials of residential post-war urban neighbourhoods.

The manuscript is structured as follows: In Section 2 we specify the state of the literature on densification and outline the original contribution and motivation of this work. Section 3 provides a detailed description of the scope of analysis and presents our methodology. Section 4 discusses the findings of our analysis and provides an outlook for further research. Conclusions and recommendations are provided in Section 5.

2. Literature overview on urban density, sustainability and densification potentials

The discourse on densification and on the relationship between urban form and sustainability is highly contentious (Jenks et al., 1996; Neuman, 2005; Schmidt-Thomé, Haybatollahi, Kypta, & Korpi, 2013). The commonly raised ‘compact-city-paradox’ for example describes the contradicting tendencies of attributing high-quality living to low-density and high sustainability to high urban density (Arundel & Ronald, 2017). The ‘paradox of intensification’ (Melia, Parkhurst, & Barton, 2011) is a similarly raised concern, which describes the effect that if population density increases, local environments suffer despite per capita sustainability gains achieved by densification. Densification in cities is a complex phenomenon and affects multiple qualities cities should have, i.e. ‘maximum levels of aesthetic and functional, economic and operational, environmental and energetic, and social and process quality’ (Cacciaguerra, 2015). Densification may have potentially conflicting impacts on either of these qualities. Sustainable densification thus needs to carefully consider and balance economic, environmental and social aspects. Increasingly, densification studies include multiple indicators, facilitated by the developments in open data availability and geographical information systems. Amer and Atiya (2019) establish sustainability criteria for decision making for roof stacking. Flores and Sosa (2017) present a raster-based spatial multi-criteria analysis based on an analytical hierarchical process for assessing the suitability of densification with help of environmental, economic and liveability variables. Cabrera-Jara, Orellana, and Hermida (2017) develop a raster-based sustainable urban densification index to determine densification sustainability. All these approaches rely on data-driven approaches which enable the spatial overlay and combination of different types of data.

As can be seen from this brief literature overview, very different densification impacts or sustainability indicators have been studied, ranging from ecological to socio-economic indicators. In the following, we discuss in more detail the energy (Section 2.1) and transport (Section 2.2) sector, which are both closely linked to urban density.

2.1. Urban density and energy

Cities having high population densities, high energy prices and high income are observed to have the lowest carbon emissions (Creutzig, Baiocchi, Bierkandt, Pichler, & Seto, 2015). It is found that urban density influences energy use as much as energy efficiency improvements, and the spatial configuration of urban areas is critical for greenhouse gas reduction (Güneralp et al., 2017). The relationship between urban density and energy is however non-trivial as urban density results in various effects such as urban heat islands, changes in shading or influences potentials for urban greening or renewable generation (Kebbahe, 2019; Mohajeri et al., 2016; Raji, Temjerlik, & van den Dobbelsteen, 2017). There is considerable literature studying impacts of urban form or urban density on energy: Chhipi-Shrestha, Hewage, and Sadiq (2017), for example, link densification to the water-energy-carbon nexus. Other authors quantify the influence of the urban form of buildings on energy demand or assess wider energy system impacts (Hargreaves, Cheng, Deshmukh, Leach, & Steemers, 2017; Perera, Coccolo, & Scartezzini, 2019). Mohajeri et al. (2019) simulate changes to energy demand and supply in a rural Swiss case study for a densification and expansion scenario. They find in the case of densification, heating demands are lower by 8–12 % by 2050 due to the solar gains from having less shading of neighbouring buildings and reduced heating loss due to the compactness of buildings. For cooling, the authors find that a densification strategy needs 3–6 % more cooling in the short term but saves 12–15 % cooling demand in the long term. Vuckovic, Loibl, Tobizer, and Stolnberger (2019) find for a densified Vienna neighbourhood reduced temperatures during daytime due to shading but slightly higher temperatures during nighttime. From an energy system perspective, the impact of urban density on energy is particularly strong because of various energy infrastructure networks (e.g. electricity grid, gas network, district heating or cooling) (Zach, Erker, & Stoeglehner, 2019). This is because the efficiency of networks is strongly influenced by effects such as economies of scale or economies of density (inter alia Alvarez, Prieto, & Zoﬁo, 2014; Zvolleff, Kocaman, Huh, & Modi, 2009).

2.2. Urban density and transport

Infrastructure networks enable the transportation of water, people, goods or energy across geographical space. It has been shown that the efficiency of network-based infrastructure is firmly linked to urban density (Siedentop & Fina, 2010) and particularly network infrastructures with high fixed delivery costs are affected by network effects (Oughton & Frias, 2018). High-density areas enable sharing infrastructure with more people, making it for example possible to achieve lower per-capita infrastructure cost or reducing per capita greenhouse gas emissions. Water distribution networks, district heating or roads are obvious examples of such types of infrastructure (Chambers, Zuberi, Jibran, Narula, & Patel, 2020; Eggimann, Truffer, & Maurer, 2016). However, also the efficiency of services that depend on the road network such as waste management are affected by urban density (Richter, Ng, Karimi, & Chang, 2021). The importance of good connectivity with transportation infrastructure is commonly highlighted in the densification literature (Ibraeova, Correia, Silva, & Antunes, 2020; UN Habitat, 2013). Densification, therefore, holds the promise of multiple advantages, particularly reducing the need for mobility if densification takes place in central and well accessible locations (Conticelli, Proli, & Tondelli, 2017). It has also been established that car ownership increases with increasing income and only for high-income cities, a decoupling of GDP and ownership was observed (Creutzig et al., 2015). However, urban density also affects vehicle ownership as with increasing urban density a trend was observed towards a lower number of vehicles per person (Van Eggermond, Erath, & Axhausen, 2016), promising lower noise and air pollution levels and improving the quality of life (Jungman et al., 2021; Roberts, 2019). Marini et al. (2019) for example use agent-based modelling to compare effects on air pollution or commuting behaviour for different densification scenarios in Switzerland. Studies such as these highlight that depending on how urban planning and the allocation of a growing population unfolds, densification strategies have far-reaching implications including on mobility and network-based transportation capabilities.

2.3. Densification in Switzerland

With a current population of 8.5 million, Switzerland is faced with population growth and limited availability of space. Swiss topography restricts the availability of suitable area for settlement which is estimated to be only around 30 % (BPS, 2005) and potential building development sites are in common competition with fertile soil used for agriculture (ARE, 2020). The recent history of urbanization in
Switzerland is complex but the overall picture is that the urbanization process has been unguided and land-intensive: A scattered, as well as a compact expansion of cities, has been the modus operandi in Switzerland, resulting in new settlements and typically the construction of single-family homes, extensive infrastructure facilities or shopping facilities in the agglomeration of Swiss cities (Herzog, De Meuron, Meili, Diener, & Schmid, 2006; Schwick & Jaeger, 2010).

It has been widely recognized that densification of the existing building stock is decisive to address the increasing housing need due to the population increase. Therefore, Swiss regulations promote inward settlement development to create compact settlements (Grams & Nebel, 2013; ILG, 2012; Swiss Confederation, 2019). Urban developments are supposed to take place where higher densities are conceivable from a spatial planning perspective, particularly in larger contiguous neighbourhoods where the development is not opposed to overriding private or public interests (Grams & Nebel, 2013). In Switzerland, different densification assessment have been performed having each a specific scope to estimate densification opportunities at a regional or national scale (Domschky, Kurath, Mühlebach, & Primas, 2016; Gams-Dietziker, 2015; ILG, 2012; Nebel, Widler, Hollenstein, & Furrer, 2012; Nebel, Hollenstein, Di Carlo, Niedermaier, & Scholl, 2017; Wüst Partner, 2018). Also, further effects of densification have been assessed for Switzerland: Hollenstein (2019) for example explores the densification impacts on primary energy demand for not yet exhausted building zones or Marini et al. (2019) study impacts on urban transport.

In Switzerland, densification is high on the political agenda and the focus of intense debates. Newly coined phrases such as ‘density stress’ or ‘growth pain’ (Hengartner & Anna, 2014) reflect existing anxieties surrounding current demographic developments. It is therefore particularly important that research contributes to the quantification and assessment of detailed and realistic opportunities for neighbourhood densification.

2.4. Original contribution and motivation

Studies on densification are usually designed regionally, for a specific city or case study neighbourhood. Some recent examples include Amer, Mustafa, Teller, Attia, and Reiter (2017), who assess roof-stacking potentials on the building level for Brussel. Bibby, Henneberry, and Halleux (2020), Wang et al. (2019) or Broitman and Koomen (2015) study densification processes at a national scale. Vuckovic et al. (2017) generate alternative 3-dimensional urban densification scenarios based on building regulations and guidelines and explore densification impacts for the mitigation of heat-island effects in a case study area of 350 × 350 m. While each of the international or Swiss studies on densification mentioned so far has a specific scope (cf. Section 2.3), they reveal several more general shortcomings:

- Densification assessments simulating the potential of additional floor area typically take on a building perspective.
- The consideration of constraints hindering the feasibility of densification projects is crude.
- Only limited spatial explicit densification potential assessments are available at a national scale relying on high-resolution modelling.
- The evaluation of densification potentials concerning sustainability is generally missing.
- The geographical location is only loosely considered to evaluate densification sites.
- Sensitivities of underlying densification assumptions are not made transparent.
- Few elaborate up-scaling methodologies have been applied to derive national results.

We take these neglected concerns as a starting point of our analysis. Our objective is to assess and evaluate sustainable post-war neighbourhood densification potentials for different densification strategies whilst considering a range of constraints to guarantee a high degree of realism. One key motivation for this focus is that the transformation of entire residential neighbourhoods as opposed to individual green-field site developments bears the opportunity to re-design urban space with respect to free space, transport, water or energy infrastructure to realise more sustainable living (Engel-Yan, Kennedy, Saiz, & Pressnail, 2005; Rohe, 2009; UN Habitat, 2015; Zhang, Yung, & Chan, 2018). Our focus on neighbourhoods potentially enables integrated planning whilst realising densification potentials, which opens up possibilities to reap long-term sustainability impacts (Boverket, 2017; Rohe, 2009; UN Habitat, 2015). We argue that this focus on post-war neighbourhoods allows a more realistic estimation of densification potentials and complements the densification literature more generally focusing on urban form or single buildings.

Building upon the previous discussion on densification and links to energy and transport in Sections 2.1 and 2.2, we note that focussing on post-war buildings is particularly promising from a sustainability point of view due to their overall poor energy performance, their large densification potentials due to their modernistic spatial layout and because post-war buildings are facing their second renovation cycle (Aksoezen, Daniel, Hassler, & Kohler, 2015; Ostermeyer, Nägeli, Heeren, & Wallbaum, 2018; Streicher et al., 2019). Addressing neighbourhoods that have currently poor energy performance consequently results in the highest sustainability gains in case of retrofitting or rebuilding and increasing the overall floor area. As we have argued, connectivity with transportation infrastructures is critical. Sustainable densification will therefore need to focus on locations with good accessibility and connectivity primary to maximize the reduction of energy-intensive transportation and to shift the modal split towards public transportation (Pacifici, Marins, Catto, Rama, & Lamour, 2017). Bearing in mind the link between urban density and infrastructure efficiency, we argue that accessibility and connectivity is a good indicator of the capability of how existing systems such as the electricity system can cope with increasing demands. Additionally, geography and population density are also important for firms for their investment decisions and roll-out in telecommunication infrastructure (Gött, 2013; Oughton & Frias, 2018).

3. Method

The most important modelling steps, major input data and assumptions of our analysis are shown in Fig. 1. The method section is structured according to the following modelling steps: First, we clarify the detailed scope of our analysis (Section 3.1), followed by data collection and preparation and the generation of buildings plots (Section 3.2) which serve as an input for the identification of post-war urban structure units (Section 3.3). The identified urban structure units are characterized in Section 3.4 and serve to identify suitable neighbourhoods. The neighbourhoods are subsequently classified into different archetypes (Section 3.5) forming the basis for the densification and up-scaling analysis to drive national statistics (Section 3.6).

3.1. Scope of analysis

The detailed scope of this analysis builds on the listed shortcomings in Section 2.4. The analysis has two distinctive focal points: First, the unit of analysis are residential neighbourhoods, as opposed to estimating densification potentials of individual buildings. Second, to derive genuine estimations of sustainable densification potentials, we consider a range of different constraining factors affecting the practicability of densification projects, namely:

- Geographical confinement to urban areas of Switzerland.
- Exclusive consideration of neighbourhoods from the post-war period (1945–1980).
Newly assigned zones for future development with currently no buildings are ignored as we focus on the densification of the existing building stock.

- Neighbourhoods that consist predominantly of single-family homes are ignored as they are not primarily suitable for densification. The key reason is that typically in such a context densification projects are challenging due to the circumstance of encountering multiple landowners aggravating the adaptation of the existing building stock in a coordinated way (Wüest Partner, 2018).

- Additional zones inside the settlement area such as graveyards, allotments or public parks are not taken into consideration. Neighbourhoods serving non-residential purposes such as industrial buildings, churches or schools are also excluded from the analysis.

- With help of geospatial information on specially protected buildings or zones, we explore the influence of potential preservation orders which potentially restrict densification.

### 3.2. Data collection and preparation

The availability of detailed building-related information is crucial for high-resolution densification analysis. We collect and combine different data from Open Street Map, Swisstopo (2019) and the Federal Building Registry (BFS, 2017) to obtain building geometries (e.g. building footprint, building height) and building attributes such as construction age, type and occupancy information. To delineate urban space and for excluding industrial zones, we use data provided by the Federal Statistical Office (BFS, 2014). Building zones are taken from a harmonized Swiss data set (ARE, 2017).

To identify entire post-war neighbourhoods, we rely on detailed building plot geometries from the cadastral plans, which are however available only for about 60 % of the study area. This limited data availability necessitates a more generic approach to generate synthetic plot geometries in case building plot data is missing. We use an Euclidian distance allocation algorithm based on segmenting each building zone into a one-meter cell size raster. Raster cells intersecting building footprints are used as seed cells to spatially assign each raster cell to the closest building. All cells belonging to the same building are subsequently spatially merged. This procedure enables to automatically generate approximate building plots with minimal input data, namely building footprints and building zones. The open-source software QGIS is used for handling geospatial data and the Python package Shapely is used for handling geospatial data and the Python package Shapely (Gillies et al., 2020) for data processing.

### 3.3. Post-war urban structure units

To locate post-war neighbourhoods, we first develop an automated geospatial procedure to identify urban structure units (USU). USU have been successfully applied in other infrastructure planning contexts (inter alia Eggimann et al., 2016; Wang et al., 2013) and can be defined as 'areas with a physiognomically homogeneous character, which are marked in the built-up area by a characteristic formation of buildings and open spaces' (Wickop, 1998). The aim is to find contiguous zones where post-war buildings dominate and which form a structural unit of analysis. From the building plots (cf. Section 3.2) all inhabited, non-single family buildings from the post-war period are selected. Buildings that are dominantly used for commercial or other uses are ignored and filtered based on the average floor area per person. The selected building plots are spatially merged with each other to form urban zones in case they are adjacent or within a distance of 30 m. In several post-processing steps, additional building plots having so far not been selected are merged in case they are fully within urban zones or in case they share large parts of their borders with the urban zones.

We use the street and rail network to help segment these obtained urban zones into USU. All intersecting railways and major streets are excluded from the created geometries and buffering is applied to derive more coherent geometries. Finally, all created USU that have unrealistically high areas per person are removed from the selection. These are typically USU containing large open fields assigned to new land development projects and thus do not fall into the scope of our analysis. Eventually, a USU makes up a neighbourhood, if based on its characterization, it fulfils the defined criteria of a neighbourhood as described in Section 3.4.3.

### 3.4. Neighbourhood analysis

#### 3.4.1. Locational characterisation

Sustainable densification will need to focus on central and well accessible locations. We classify the locational centrality and accessibility of each USU as ‘low’, ‘medium’ or ‘high’. The semantic description of place with terms such as central or peripheral is conceptually challenging (Purves, Winter, & Kuhn, 2019). Therefore, we evaluate the geographical location of each USU based on a fuzzy analytic hierarchy...
process: We spatially intersect two geospatial datasets which provide information on public transport accessibility and transportation time to urban centres (ARE, 2019) to evaluate point-based categorical accessibility (Table 1). If multiple accessibility classes are assigned to an USU, the class with the largest spatially intersecting area is used. Fig. 2 shows the resulting accessibility and centrality classification for an example region.

### 3.4.2. Neighbourhood type characterization

With the increased availability of geospatial data, a range of different indicators has been developed to characterize and classify the urban built form for a range of different applications including cartography or spatial planning (Berghauer Pont et al., 2019; Bobkova, Berghauer Pont, & Marcus, 2019; de Smet & Teller, 2016; Lüscher, Weibel, & Burghardt, 2009). Whereas the urban environment has extensively been characterized based on structural attributes particularly in ecological studies, the inclusion of man-made elements is more recent (Stokes & Seto, 2019). Usually, urban form is characterized by morphological and topological criteria of buildings and zones containing multiple buildings. Meinel, Hecht, and Herold (2009) for example list an extensive collection of building and neighbourhood indicators. A variety of different options are available to describe our derived post-war neighbourhoods, such as the street characteristics, neighbourhood area properties, socio-economic or ecological parameters (cf. Meinel, Hecht, Herold, & Schiller, 2008). However, many criteria may be hard to reliably calculate due to data limitations or may be highly correlated with each other. For this analysis, we resort to standard variables that have been used successfully in previous studies (Bobkova, Marcus, Berghauer Pont, Stavroulaki, & Bolin, 2019; Meinel et al., 2009; Steiner, Lange, Burghardt, & Weibel, 2008; Werder, Kieler, & Sester, 2010). We use the information on the building age and building type for identifying suitable USU and use demographic and morphological criteria for detailed characterization of the derived neighbourhoods, in doing so going beyond the characterization of individual buildings. The used descriptive variables (cf. Table 2) are calculated as follows:

\[
\begin{align*}
    f_1 &= \frac{BB_A - B_A}{BB_A} \quad (1) \\
    f_2 &= \frac{BB_A \times BB_{pr}}{BB_A} \quad (2) \\
    f_3 &= \frac{2 \times \sqrt{B_A / \pi}}{BB_A} \quad (3) \\
    f_4 &= \frac{N_A}{NGVA} \quad (4) \\
    f_5 &= \frac{N_{POP}}{N_A} \quad (5)
\end{align*}
\]

where BB_A is the bounding box area, B_A the building footprint area, BB_{pr} the minimum bounding box polygon side, B_l the building area, BB_r the radius of the bounding box, N_A the neighbourhood area, NGVA the building floor area, N_{POP} the neighbourhood population and NGVA the neighbourhood gross floor area.

### 3.4.3. Neighbourhood selection

In this step, all USU fulfilling the definition of a neighbourhood are identified. There is no clear scientific definition of what constitutes a neighbourhood from a dimensional point of view (Park & Rogers, 2015). The definition depends strongly on the geographical context: For Switzerland, other authors list examples of neighbourhoods typically in the range of 150–500 occupants (inter alia Domshchy, Kurath, Mühlebach, & Primas, 2018). We settle on a minimum number of occupants of 200. To include very small neighbourhoods and for sensitivity considerations, we assume an even lower minimum occupant size of 150. For selecting USU, we use two different approaches based on the minimum floor area (\(GFA_{min}\)) and urban density \(GFA_{density}\) which allows exploring the sensitivity of how neighbourhoods are defined:

- The average floor area per person in Switzerland is ~46 m² (Federal Statistical Office, 2020). To derive the gross floor area (GFA) which includes space used for stairs, cellars or walls, we apply a factor of 1.2 (Statistik Stadt Zürich, 2005). This results in an average of 55 m² GFA per person. Based on the minimum number of neighbourhood occupants \(p_{min}\), the respective minimum neighbourhood GFA is calculated as given in Eq. 6:

\[
GFA_{floor} = p_{min} \times 46 \text{ m}^2 \times 1.2
\]

- For Swiss cities, an urban density of 150 persons per hectare can be considered as dense, which corresponds to a gross floor area ratio of about 85 % (ARE Kanton Zürich, 2015). We assume this minimal gross floor area ratio to hold true for our neighbourhoods and calculate the minimum neighbourhood GFA as given in Eq. 7:

\[
GFA_{density} = \frac{p_{min} \times 46 \text{m}^2 \times 1.2}{0.85}
\]

After the identification of all neighbourhoods according to these criteria, some resulting neighbourhoods are very large and very heterogeneous. Therefore, neighbourhoods are spatially intersected with the minor road network which provides a refined segmentation of neighbourhoods improving the neighbourhood archetype classification as outlined in Section 3.5.

### 3.4.4. Protected buildings and zones

Taking into account the potentially complicating effects on densification caused by listed buildings or listed zones is challenging due to the lack of generally available data. Since national official cadastre data listing buildings or zones where potentially strict regulations apply are not readily available, we resort to a case study analysis of the Canton of Bern (Kanton Bern, 2019). Protected zones and buildings potentially worthy to preserve are intersected with the identified neighbourhoods. A first estimate reveals that about 3.6 % of all identified buildings within post-war neighbourhoods potentially have a preservation order. Adding all buildings which also fall into specially protected zones, the total affected population increases to 4.7 %. These regional estimates enable a first evaluation of the potential impact preservation orders might have. However, a more in-depth analysis is needed with more complete data.

### Table 1

| Travel time to centre | Transport grade | Urban centrality classification |
|----------------------|-----------------|--------------------------------|
| Minutes       | Points | Class | Points | Category |
| 0 – 10        | 3      | A     | 4      | 7        | high     |
| 10 – 20       | 2      | B     | 3      | 4 - 6    | medium   |
| 20 – 40       | 1      | C     | 2      | 0 – 3    | low      |
| 40 – 80       | 0      | D     | 1      | –        | –        |
| > 80          | 0      | –     | 0      | –        | –        |

Variables that are based on individual building properties \(f_1, f_2, f_3\) are calculated across all neighbourhood buildings and weighted with the building occupancy. The building morphology variables capture different building morphology aspects such as compactness or elongation. The Schumm’s index \(f_5\) as defined by Maceachren (1985) provides the relationship between the radius of the circle of the same area as the building divided by the radius of the circumscribing circle.
3.5. Archetype based up-scaling analysis

For practical reasons, detailed architectural densification studies are not possible for all individually identified neighbourhoods. Therefore, we need to find groups of representative neighbourhoods that allow performing representative densification case studies. This grouping of neighbourhoods enables to derive estimates at a larger scale, i.e. to perform a national up-scaling analysis (Tardioli, Kerrigan, Oates, O’Donnell, & Finn, 2018). There are different up-scaling methodologies, of which the most basic procedure is to establish a statistical relationship between the variable of interest (in this case densification potential) and another measure such as population density (Eggimann, Truffer, Feldmann, & Maurer, 2018). Hargreaves (2015) for example applies a methodology to assign representative buildings with common distinct characteristics, i.e. archetypes, based on population density.

For more elaborate upscaling techniques, either unsupervised clustering or supervised classification can be used to structure data into different clusters or classes. With unsupervised cluster analysis, such as the commonly used agglomerative hierarchical clustering or k-means algorithm, the number of clusters can ideally be inferred from the underlyng data structure. Upscaling based on unsupervised clustering methods does not rely on a priori characterization of archetypes. For Switzerland, clustering techniques have been applied at the building level (Geyer & Schlueter, 2017; Murray, Marquant, Niffeler, Mavromatidis, & Orehouning, 2020; Schirmer & Axhausen, 2016; Tardioli et al., 2018). We have explored different unsupervised clustering approaches with various neighbourhood feature combinations to test whether our identified neighbourhoods could be clearly separated. However, no distinguishable and meaningful clusters which represent typical neighbourhoods could be detected. Converting the clustering into a classification problem by matching clustering results to predefined archetypes also did not yield good enough results. We therefore resort to supervised classification, where we classify the located post-war neighbourhoods into different a priori defined representative neighbourhood archetypes.

3.5.1. Archetype definition

The urban built form varies considerably across different geographical contexts (Berghauser Pont et al., 2019; Bobkova, Berghauser Pont et al., 2019). Building and neighbourhood archetypes have been prominently applied in the energy simulation domain to consider variation in the urban form (De Jaeger, Reyniers, Callebaut, & Saelens, 2020; Murray et al., 2020; Streicher et al., 2019). Archetypes are particularly useful to simplify and generalize the urban building stock, typically because of limited computational power or in the case of being able to perform only limited detailed analysis due to time constraints. Here, our primary motivation for using archetypes is the challenge of creating a large number of detailed urban design studies for different densification scenarios and to upscale to the national scale (cf. Section 3.6). Based on expert knowledge, we define different post-war neighbourhood archetypes each having distinct characteristics for Switzerland. The archetypes are developed for Switzerland but an analogous analysis could be carried out for other geographic contexts. An analysis in another country would of course require an adaptation of the archetype definitions to fit the local context.

The defined archetypes can be differentiated from an architectural and urban design point of view and their identification is carried out manually using two different approaches in parallel: On the one hand by analysing the cadastral plans with the located post-war neighbourhoods in the metropolitan areas of Basel, Bern, Geneva, Lugano and Zürich and on the other hand by literature research on existing housing estates of the post-war period. To differentiate between the neighbourhoods, we consider various characteristics, such as building typologies, the spatial relationship between the buildings or the spatial relationship between the buildings and their surroundings (Table 3) and define the following archetypes:

- **A1**: Large iconic monolithic building structures
- **A2**: Compositional ensembles of solitary buildings
- **A3**: Compositional ensembles as clusters of similar buildings
- **A4**: Linear housing and open city block structures
- **A5**: Heterogeneous detached apartment buildings

The archetypes A1, A2 and A3 are mainly large-scale housing estates (so-called ‘Grands Ensembles’) and were primarily built in the 1960s and 1970s.
identified real-world examples of the archetypes A1 — A5 used for classification and are provided in the Supplementary Material (SM) Note 1 (Appendix A).

### 3.5.2. Archetype classification

Whereas for example Steiniger et al. (2008) classified the Swiss building stock with help of machine learning algorithms into categories such as urban or rural, we apply supervised classification algorithms to the predefined archetypical post-war neighbourhoods A1 — A5. Supervised classification depends on the choice of algorithm, algorithm-specific parameters, the data scaling, the training sample or the number and selection of feature variables (Tardioli et al., 2018). The choice of variables describing the underlying data is crucial, as it influences how much weight is attributed to a certain feature. For example, using many variables describing the urban form assigns more weight to morphological characteristics. As the supervised classification of highly multi-dimensional data is challenging, typically not more than a handful of feature variables are used for classification as relying on a small number of variables reduces the need to acquire large training datasets. A further complication is high collinearity between variables. With the help of dimensionality reduction techniques such as principal component analysis, the collinearity can be addressed and the number of parameters reduced to principal components (Duda, Hart, & Stork, 2001). For our analysis, we rely on the feature variables listed in Table 2 to describe the neighbourhoods.

We explore different classification algorithms such as support vector machine or random forest, different data scaling methods and feature variable combinations. As the value ranges across the different variables is very different and the variable units incomparable, we transform our feature space values by scaling to values from 0 to 1. Because we have an imbalanced dataset, accuracy is not a good measure and we resort to the F-measure for the cross-validation. We tune our hyperparameters with a grid search to provide the best parameter combinations and explore the plausibility of the classification results by cross and face validation. The used classification algorithms are employed with the python based scikit-learn package (Varoquaux et al., 2015). The geolocation of the identified real-world examples of the archetypes A1 — A5 used for classification are provided in the Supplementary Material (SM) Note 1 (Appendix A).

### 3.6. Densification analysis

Domschky et al. (2018) collected information on post-war densification case studies for entire neighbourhoods in Switzerland. Across their case studies, the change in population due to densification measures range from a few percentages to up to double the number of inhabitants. Generally, they find that existing neighbourhoods with low densities show more potential than neighbourhoods with currently already high densities. Densification thus depends on the case study context as well as on the overall strategy. In this analysis, three characteristic densification strategies are explored:

**S1:** ‘Below-average’ densification strategy through renovation, increase in height, extension or supplementary buildings to reach current average archetype specific densities. In this strategy, only neighbourhoods with below-average floor-area ratios are densified to current average floor area ratios.

**S2:** Business as usual’ densification strategy through the replacement of existing buildings either as a whole or in phases in accordance with the currently common adaptation of building zones.

**S3:** ‘Concentrated densification’ strategy through the replacement of existing buildings either as a whole or in stages with a maximum density based on contemporary urban development criteria (not in compliance with current legislation).

The densification strategies are schematically visualized in Fig. 3. Wherever possible, for each strategy and archetype, current and future densities are assessed based on literature case studies and own urban designs. The densification strategies aim for a spatial improvement and qualitative incorporation of the surrounding context. Fig. 4 lists all used case studies that have been used to calculate densification potentials per archetype and densification strategy. For strategy S1, average current floor area ratios (FAR) are calculated per archetype based on the supervised archetype classification. For strategy S2 and S3, a linear relationship is fitted between current and future floor area ratios, which allows estimating neighbourhood specific future densities in relation to current density values. When calculating future densities, a maximum density is assumed (FAR\textsubscript{max}) which corresponds to the maximum assessed FAR value per archetype and strategy. For archetype A1, we assume that densification is not possible as these neighbourhoods are commonly listed. Similarly, we assume that densification strategy S3 is not applicable for archetype A5, as this archetype, due to its ownership structure, is for the most part confronted with the same hurdles as the single-family home neighbourhoods. It is therefore assumed for strategy S3 and archetype A5 that the densification takes place in the same way as for strategy S2. The detailed urban designs are provided in SM Note 2. Potentials are calculated by multiplying current neighbourhood population with the ratio of future to current FAR.

### 4. Results and discussion

#### 4.1. Geographic location

The geographical location concerning the centrality and accessibility is shown in Fig. 5 for all identified Swiss neighbourhoods. Densities between 150—300 inhabitants per hectare can be considered as high, densities above 300 as very high (ARE Kanton Zürich, 2015). The evaluation of the geographical location differs across the population density range: Whereas neighbourhoods having currently lower population density values are more often situated in less central locations,
centrally located neighbourhoods reach typically higher population density values. A first general finding is that potential areas with currently low densities and therefore high densification potentials are on average less suited from a locational and thus sustainability point of view. However, we find also neighbourhoods with relatively low population densities and good overall accessibility which are interesting neighbourhoods for densification. This considerable spatial differentiation of the post-war neighbourhoods in terms of their geography allows for good prioritising concerning sustainability implications.

4.2. Archetype analysis

The most plausible classification of neighbourhood archetypes was obtained with a support vector machine and random forest classifier (cf. Section 3.5.2). To include the sensitivity of the neighbourhood classification, we combine principal component analysis (having 3 principal components) with the two classification algorithms. This provides us with in total 4 different approaches for which the resulting floor area per archetype is shown in Fig. 6. Even though we observe a consistent pattern of the different classifications, we note particular differences in classification frequencies for the archetypes A1, A3 and A4. The difference in the classification results reflects the challenge of capturing important architectural and urban elements such as façade orientation or building orientations, which we do not capture directly with our feature variables. Also, there is no standard delineation (i.e. in terms of morphology or building heights) of different archetypes and their definition is fuzzy. The heterogeneity of buildings within neighbourhoods further complicates the neighbourhood classification as opposed to, e.g. the classification of individual buildings. Additionally, we only consider residential post-war buildings, which means that the
4.3. Archetypical up-scaling

Total Swiss densification potentials per densification strategy, as well as the distribution in relation to the accessibility and centrality, are shown in Fig. 7. Average densification potentials range across the densification strategies between 0.35–1.24 million people (corresponding to between 4–15% of the current population). The centrality and accessibility are high for about 8–17% of the potential and low for about 36–39%. As expected, densification potentials are largest for the densification strategy S3 and smallest for the strategy S1. However, the differences are considerable, particularly between strategy S2 and S3. This highlights that there is considerable room for manoeuvre when setting maximum densification regulations.

We note that for the locations with high centrality, the densification potentials are relatively small across all densification strategies. Given their economic importance due to their profitable location, many neighbourhoods already have high densities and/or have been densified. Even if neighbourhoods with low centrality and accessibility have potential especially, if a concentrated densification strategy is adapted, these neighbourhoods should not be given priority from a sustainability perspective. The most interesting potentials are therefore neighbourhoods with medium urban centrality and accessibility. We find that there are many such neighbourhoods where particularly high potentials could be realised if a concentrated densification strategy (S3) were implemented. If only implementing a business-as-usual densification strategy (S2), the resulting potentials are much lower. We, argue that it would be a missed opportunity for these neighbourhoods if a business-as-usual densification strategy were to be pursued.

We note considerable methodological uncertainties as both the parametrization of the neighbourhood concept as well as the neighbourhood archetypes are imprecise, i.e. there are no unequivocal definitions. Furthermore, the classification of the archetypes depends on the supervised classification approach. These uncertainties reveal that for densification potential analysis, calculated numbers are not fixed but depend on a range of different assumptions and show the importance of communicating them.

Simulated densification potentials vary considerably across administrative boundaries. As expected, the largest and most urban cantons such as Zürich (ZH), Bern (BE) or Geneva (GE) have the highest potentials in absolute terms. In relative terms, there is also considerable potential in cantons such as Zug (ZG) or Neuchâtel (NE) which supports the focus shift away from the main urban centres. The high-resolution overview of the densification potential on a community level in Fig. 8 (also see SM Note 3 for cantonal results) reveals that the overall pattern is similar across the different densification strategies. However, densification potentials are not distributed evenly across space: When comparing the centrality of the calculated potential in Fig. 9, we note that particularly communities next to core-city centres have many neighbourhoods with medium centrality and accessibility, which could potentially accommodate a considerable amount of additional inhabitants (>20% of the current population). At the same time, we note that the potential resulting from neighbourhoods having a high centrality and accessibility is located in only a few communities.

When comparing our results with existing studies, the scope of the respective analysis must be considered: Wüest Partner (2018) for example estimate that within all existing Swiss developed and undeveloped building zones, there is room for an additional 2.59 million people. Nebel et al. (2017) estimate an overall Swiss densification potential of between 0.7–1.4 million people when considering undeveloped land reserves and the transformation of industrial sites. When only considering inward land-use reserves and the densification of already built sites or maximum densities according to current regulations, they estimate a potential of 0.36 – 0.91 million people. This compares well with our calculated densification potential for our business-as-usual densification strategy (S2), where we estimate an average potential of 0.6 million people. Generally, we confirm the pattern that urban centres and agglomerations also show the highest potential when focusing on the sustainable densification of post-war neighbourhoods (Nebel et al., 2012; Wüest Partner, 2018).
4.4. An illustrative example of densification impacts on energy

The following illustrative example showcases how findings from this study can be used for rough explorations of potential densification implications. Our analysis enables a comparison of energy demands or land-use change for a densification scenario versus an urban sprawl scenario. Let us assume that for a densification scenario an additional 0.35–1.4 million people would be accommodated in post-war neighbourhoods in Switzerland. For an urban sprawl scenario, new single- or multi-family buildings would be built at the fringes of the current settlement areas. In Switzerland, there is a trend for lower per capita floor area values in central locations and also corporative housing have typically lower values and are oftentimes from the post-war period. The Swiss average floor area per person for new buildings is \( \sim 46 \, \text{m}^2 \), \( \sim 52 \, \text{m}^2 \) for single-family homes and \( \sim 47 \, \text{m}^2 \) for multi-family homes (Federal Statistical Office, 2020). Assuming single-family homes for the urban sprawl scenario, this means that an additional 18–73 km\(^2\) of floor area would have to be built on new greenfield sites, which could have been saved from construction compared to the densification scenario. Even though additional land would also be required for a densification scenario, this land would be located only within existing already built-up neighbourhoods. Also, this land demand consumption would be considerably lower due to the lower per capita floor area values.

In terms of operational energy, let us assume an operational annual energy demand for suburban single-family homes of 54 kW h/m\(^2\) and...
34 kW h/m² for densified urban post-war neighbourhoods (demands according to Streicher et al., 2019). The reduced overall floor area of 6 m² per person in the case of the densification scenario (2.1–8.4 km²) is responsible for 0.1–0.4 TW h of annual energy savings. Annual operational energy demand savings due to lower demand per m² range between 0.3–1.3 TW h. A densification scenario would thus lead to combined overall annual operational energy savings of 0.4–1.7 TW h. The energy effects of neighbourhood densification will however depend not only on the floor areas but also on the structural characteristics, the location, the type of building retrofit or how much of the existing resources can be recycled (Churkina et al., 2020). The quantification of possible further benefits due to savings in embodied energy savings or energy implications from changes in urban mobility is however more challenging.

4.5. Limitations and research opportunities

Our analysis reveals several limitations and research opportunities that could be assessed in follow-up studies to improve and extend the presented analysis.

The localisation of potential densification neighbourhood sites necessitates good data availability, particularly up-to-date building attributes (i.e. construction age, number of floors, or refurbishment status) and ideally cadastre data with precise plot geometries. We ignored currently already refurbished and renovated post-war neighbourhoods, as our building dataset does not include information on refurbishment. As a consequence, estimated potentials may be lower as already some post-war neighbourhoods have undergone refurbishment or densification. Our estimations assume no change in the mix between residential and non-residential use of the neighbourhoods for each densification scenarios. The availability of further data indicating the feasibility for densification, e.g. related to noise, building ownership or the preservation status would further improve the analysis. More case study data or additional urban designs would improve the relationship between densification strategies and archetypes. However, detailed urban design of case studies to define densification strategies is laborious and automated procedures could be explored. Further analysis could also focus on the definition of additional densification strategies, such as strategies allowing even higher densities in particularly suitable locations. Alternatively, if high-resolution information on current maximum densities based on current regulations were available, remaining potentials according to current regulations could be estimated more accurately.

Whereas structural densification typically is the result of constructing additional living space for a given area by measures such as urban infill or roof-stacking, per capita living space can also be reduced by other measures such as the moving of empty nesters or reducing the per capita living space (Stieß, Umbach-Daniel, & Fischer, 2019). We only considered structural densification, i.e. we assumed constant changes in per capita floor area within the neighbourhoods over time. Reducing living space is however a far-reaching social innovation, necessitating broad transformations of culturally established norms.

We have used centrality and accessibility as sustainability indicators for the assessment of neighbourhoods. They serve as indicators for the sustainability of a location’s densification. However, location alone does not capture the full range of possible sustainability indicators. More
detailed sustainability indicators such as energy, costs, emissions or water consumption over the entire life cycle could be investigated (Churkin et al., 2020). The presented geospatial framework based on the identified archetypes could however be easily extended for the quantification of a full range of other densification impacts. Finally, our performed quantitative analysis of densification potentials needs to be followed by more qualitative assessments of densification potentials focusing on other factors such as architectural qualities or the embedding of densification projects in the wider socio-economic context to realise highly livable densified neighbourhoods (Boverker, 2017; Cabrera-Jara et al., 2017; Flores & Sosa, 2017; VLP-ASPAN, 2015). Also, more attention could be given for example to urban greening for preventing the densification-paradox or providing more qualitative densification potentials (Kyttä, Broberg, Tzoulas, & Snabb, 2013).

5. Conclusion

Urban densification of entire neighbourhoods is an opportunity to tackle multiple environmental challenges whilst addressing current urbanization trends. Transforming already built-up residential neighbourhoods by recycling land is critical when creating space for an increasing population given limited land resources (Greenstein & Sungu-Eryilmaz, 2004). This study presents a geospatial data-driven framework for spatial explicit quantification and evaluation of densification potentials which can be applied in different geographical contexts and adapted to local data availability. Our analysis enables to automatically locate and classify different neighbourhood archetypes which allow the definition of specific densification strategies for different archetypes. We have argued that as opposed to greenfield land development, sustainable land development should take into account the existing building stock or other critical infrastructure such as the transportation system. Our analysis allows the prioritisation of neighbourhoods concerning the geographic location and focuses on post-war neighbourhoods which allows assessing detailed and realistic densification potentials. Post-war neighbourhoods are found in different geographical locations and they are particularly interesting for densification due to their necessary second renovation cycle, and their overall poor energy performance which provides a window of opportunity for energy sensitive densification and building retrofit. We have proposed a neighbourhood focus, as focusing on the transformation of entire neighbourhoods allows for integrative planning. Considering further planning aspects such as the use of free space for greening or the rethinking of the transportation infrastructure is an opportunity to improve sustainability and high-quality living.

Based on our Swiss case study, we conclude that the presented methodology allows to effectively assess densification potentials for post-war neighbourhoods at a larger geographical scale. We simulate densification potentials in case of a business-as-usual densification strategy and in case current policies would allow for higher densities for neighbourhoods. It turned out that the densification potential in highly central locations is limited. However, we have identified considerable potential in locations with medium centrality and accessibility. We believe that it would be a lost opportunity to pursue a business-as-usual densification strategy instead of realising higher densities in these neighbourhoods. Depending on the pursued densification strategy, an additional 0.35–1.4 million people (4–15 % of the current Swiss population) could be accommodated in Switzerland within post-war urban neighbourhoods. A densification potential of around 0.7 million people is estimated for the business as usual densification. For the concentrated densification strategy, the estimate is about 1.4 million people. Across all scenarios, we estimate that more than half of this potential is located in favourable locations which should be considered first to explore sustainable densification. While the detected potentials are Swiss specific, the lessons learnt generally hold also true for other countries. Densification potential may vary considerably across space and the accessibility and connectivity of neighbourhoods provide valuable information on how neighbourhoods are embedded into other infrastructures such as transport. Also, the archetype based approach enables to perform densification analysis for entire countries, addressing the challenge of not being able to generate a very large number of urban designs. Particularly in other countries where former industrial sites for densification are becoming scarce, our analysis reveals that there is potentially considerable densification potential also in already built-up inhabited neighbourhoods. While our assessment allows for the simulation of densification potentials, fully reaping these potentials may require considerable institutional and policy innovation to facilitate neighbourhood transformations at larger scales.

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.

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Appendix A. Supplementary data

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