Sustainable urban densification potentials: a geospatial analysis of Swiss post-war neighbourhoods

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Abstract. Densification is a sustainable urbanization strategy for reducing per capita environmental impacts facilitating the achievement of sustainable cities as outlined in the sustainable development goals. We have developed a methodology for assessing sustainable densification potentials at a national scale based on urban structure units and perform an analysis for residential Switzerland. In contrast to single-building assessments, our methodology allows a differentiated spatial identification and evaluation of entire neighbourhoods. We focus on urban post-war neighbourhoods, which are of key importance for realising sustainable densification. Depending on the chosen methodological assumptions, between 1.1 - 1.6 million people are currently living in post-war neighbourhoods in Switzerland. We further classify post-war neighbourhoods into different geographical centrality classes to evaluate the suitability for densification from a sustainability point of view. We have calculated a first estimate of densification potentials of post-war neighbourhoods, i.e. the number of additional inhabitant which could be accommodated, across a range of density values. We estimate, that densifying post-war neighbourhoods to a minimum density value of 200 inhabitants per hectare building zone would enable the accommodation of an additional 4 – 10% of today’s Swiss population. More than half of this potential is located in central or very central urbanised geographical locations and thus most interesting from a sustainability point of view.

1. Introduction

Building sustainable cities, as set in the Sustainable Development Goal number 11 by the United Nations [1], requires sustainable urbanization and a reduction of per capita environmental impacts of living in cities. As of today, urban areas are however expanding faster than their population and in most OECD countries, as a result of urban sprawl, the percentage of very low density living areas is increasing [2]. The reduced resource efficiency due to urban sprawl leads to environmental problems such as increasing per capita greenhouse gas emissions. Densification (also urban consolidation or redensification) is therefore put forward as a strategy for the efficient use of limited living space and to realise compact cities as opposed to sprawling cities. Sustainable densification holds the promise of multiple advantages, particularly reducing the need for car traffic if densification takes place in central and well accessible locations [3]. Different types of densities can be distinguished [4] and the increase of inhabitants per area due to construction measures, i.e. structural densification, is only one aspect of densification. Whereas structural densification typically is the result of constructing additional living space for a given area by measures such as urban infill, replacement construction or roof-stacking, per capita living space can also be reduced by other measures such as the moving of empty nesters [5].
In case of Switzerland with a current population of approximately 8.5 million, the country is faced with increasing population growth and constrained availability of building space which necessitates to considerably densify in existing urbanized areas to prevent urban expansion. Urban densification is therefore an opportunity for reducing greenhouse gases as emissions are largest in cities and urbanization trends in Switzerland continue. However, a scattered expansion of cities has often been the modus operandi, typically leading to new settlements and the construction of new buildings in the agglomeration of Swiss cities. Given today's limited availability of space, densification of the existing building stock is the only viable solution to accommodate an increasing population [6] and Swiss regulations promote intra-urban densification and the creation of compact development [7]. However, only limited analysis is available at a national scale on densification potentials particularly taking into account sustainability implications as well as focusing on whole neighbourhoods as opposed to individual building measures.

This paper introduces a methodology to assess densification potentials at a neighbourhood scale with help of urban structure units (USU) which can be up-scaled to the urban area of Switzerland. Our proposed methodology considers a range of constraints which help to calculate realistic potentials and considers the geographical location to assess the suitability of each neighbourhood. The remaining of the manuscript is structured as follows: In Section 2, we provide a methodological overview. In Section 3, we discuss the methodological sensitivity of our analysis and show the calculation results of the densification potentials for the whole of Switzerland. Section 4 concludes with the key findings.

2. Method
A high-level schematic overview of the major methodological steps is shown in Figure 1. After outlining the scope of analysis in Section 2.1, we firstly identify neighbourhoods with a geospatial analysis of the existing urban building stock in Section 2.2. We characterize the accessibility of the derived neighbourhoods in Section 2.3. In Section 2.4, we perform an upscaling analysis for the whole urban area of Switzerland and calculate densification potentials for different degrees of densification.

Figure 1. Overview of the main methodological steps for assessing sustainable densification potentials of Switzerland.

2.1. Scope of analysis
The goal of this study is to make a realistic estimation of structural densification potentials by considering a range of different constraints which influence the practicability of densification projects in Switzerland. Hence, rather than performing a purely hypothetically analysis on theoretical overall densification potentials, we particularly aim to provide insight into sustainable densification, thus including sustainability criteria for calculating densification potentials [8]. As opposed to focusing on single buildings, our focus is on neighbourhoods, i.e. clusters of buildings. The following key constraints are included to provide a genuine estimate of Swiss sustainable densification potentials:

- Sustainable densification will need to focus on locations with good public transport accessibility and connectivity primary to maximize the reduction of energy-intensive transportation. For our assessment, we therefore consider the geographical location of each potential neighbourhood. We
combine two datasets providing information on public transport accessibility and transportation time to centres to classify all neighbourhoods into very central, central and peripheral neighbourhoods [9] (cf. Section 2.2).

- Our methodology focuses on the identification of residential neighbourhoods from the post-war period (1945 – 1980) as post-war neighbourhoods are particularly suitable from a sustainability point of view for densification due to their overall poor energy performance. Post-war neighbourhoods are also interesting as they have large potentials for densification due to their modernistic typological arrangement. Building age information is taken from the Federal Building Registry [10].

- We confine our analysis to urban Switzerland. To delineate urban space, we use data provided by the Federal Statistical Office [11]. Industrial zones are excluded from our analysis als based on the same data source.

- The focus of this analysis is the densification of the existing building stock. Newly assigned zones for future development with currently no buildings on it are therefore ignored. We combine different data from Open Street Map, Swisstopo [12] and from the federal building registry [10] to derive building geometries and their attributes.

- All neighbourhoods that consist predominantly of single-family homes are excluded. 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.

- Additional zones inside the settlement area such as graveyards, allotments or public parks are neglected.

2.2. Geospatial analysis

In order to locate post-war neighbourhoods, we develop an automated procedure to identify urban structure units with help of geographical information systems [13]. USU 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’ [14]. We consequently spatially define units of analysis considering the urban structure, thus going beyond individual buildings [15]. In addition to the built form, we also include the corresponding plots on which buildings are located and their attributes. The procedure thus aims to find contiguous zones where post-war buildings dominate and which form a structural unit of analysis.

In order to attain this, in a first methodological step, building plot geometries are generated for each building. Even though plot geometries from the cadastral survey would be a good starting point for our analysis, limited data availability across our whole study area necessitates a more generic approach. We therefore use a Euclidian distance allocation algorithm which segments each building zone into a raster with a one meter cell-size resolution. Raster-cells intersecting building footprints are used as seed-cells to spatially assign each raster cell to the closest building. In the following, all cells belonging to the same building are merged. This procedure enables to automatically generate approximate building plots with minimal input data such as building footprints and settlement area or building zones.

In a second step, the generated building plots serve as basic units for generating post-war building neighbourhoods. Building plots are considered based on the building properties of the corresponding building: All inhabited and non-single family building plots with a post-war construction age are selected and spatially merged with each other in case they are adjacent or within a defined spatial distance. In several post-processing steps, additional buildings plots having so far not been selected are merged in case they are fully contained in a post-war neighbourhood or in case they share large parts of their
building plot borders with the generated post-war neighbourhoods. Additionally, buffering is applied to the geometries to derive more coherent geometries. Inhabited non-single family homes with a post-war age in working zones which are adjacent to defined neighbourhoods are added as well. Furthermore, we exclude intersecting street geometries from the derived USU with help of buffering major road line geometries. Finally, a selection of the USU is made based on different criteria such as the minimum building floor area, number of people or number of buildings within the unit to derive neighbourhoods. Three different sets of methodological assumptions (low, base, high) are defined to explore the sensitivity of our calculations (see Table 1).

Table 1. Different set of assumptions are used to explore the methodological uncertainty of the quantification and upscaling of our analysis.

| Model parameter                  | Methodological assumptions |
|----------------------------------|----------------------------|
|                                  | low | base | high |
| Minimum number of inhabitants per USU | 8   | 10   | 15   |
| Minimum number of buildings per USU     | 3   | 4    | 6    |
| Minimum floor area per USU           | 15,000 | 10,000 | 8,000 |
| Neighbourhood merge maximum distance | 5   | 10   | 15   |

2.3. Geographical characterization of post-war neighbourhood

With increased availability of geospatial data, a range of indicators and methods have been developed to characterize and classify the urban built form for a range of different applications including cartography or spatial planning [16–18]. Morphological as well as topological criteria can be used to characterise the derived urban structure units for further describing the derived neighbourhoods. For this analysis, we classify the neighbourhoods into different accessibility classes which serve as an indicator on the sustainability for densification projects of each neighbourhood. Based on information on public transport time to centres as well as existing accessibility classes of public transport, all neighbourhoods are classified into very central, central and peripheral categories (see Table 2) [9]. If a post-war neighbourhood falls into different accessibility classes, the dominant class is used based on the intersected area. Figure 2 shows the underlying data for the classification into different centrality classes for an example region.

Table 2. Methodology to evaluate the accessibility and location of post-war neighbourhoods with help of travel time to centres and the public transportation grade [9].

| Travel time to center Minutes | Transport grade Class | Transport grade Points | Centrality classification |
|------------------------------|-----------------------|------------------------|---------------------------|
| 0 - 10                       | A                     | 3                      | 4 | 7 | very central |
| 10 - 20                      | B                     | 2                      | 3 | 4 - 6 | central |
| 20 - 40                      | C                     | 1                      | 2 | 0 - 3 | peripheral |
| 40 - 80                      | D                     | 0                      | 1 | -    | - |
| <80                          | -                     | -                      | - | -    | - |
2.4. Upscaling analysis
After the identification of post-war neighbourhoods and their geographic characterization, we calculate the population density (inhabitants per hectare building zone) of each neighbourhood for the whole of Switzerland as a proxy for the use density. Whereas typically the use density is defined as the number of inhabitants and employees per hectare building zone [19], we only use the number of inhabitants as we lack the information of employees. The distribution of the current density allows us to estimate densification potentials in case of the transformation of post-war neighbourhoods. Domschky et al [20] collected information on post-war densification case-studies for entire neighbourhoods in Switzerland. For their case-studies, the change in population due to densification measures range from a few percentages to up to doubling the number of inhabitants. Generally, existing neighbourhoods with low densities show more potential than neighbourhoods with already high realised densities.

In order to showcase the potential of our methodological approach, we perform an explorative upscaling analysis of sustainable densification potentials for Switzerland. The potential is calculated based on the transformation of the current post-war neighbourhood to minimum population densities. For urban Switzerland, everything above 300 inhabitants per hectare can be considered as very dense and neighbourhoods with more than 150 inhabitants per hectare can be considered as dense areas [19]. We therefore calculate the population which could be additionally accommodated if all neighbourhoods below a minimum density were to be densified to higher density values. We perform this calculation up to a population density of 300 inhabitants per hectare, where nearly 100% of the neighbourhoods would need to be transformed (results are shown in Figure 4).

3. Results
The underlying basic unit of analysis for our national densification analysis are post-war urban structure units. Figure 3 shows exemplary results of our automated geo-spatial algorithm to identify post-war USU compared to a manual identification, where the delineation of post-war neighbourhoods was performed based on expert knowledge. In general, we notice that in case of a manual identification of USU, the defined units generally include more public buildings and buildings which do not belong to the defined post-war construction period. Also, often single-family homes are included in the defined perimeters. In case of manual classification, the urban structure units follow more dominantly the primary road networks. In case of an automatic generation, units may extend across roads even for a single or a few buildings in case they match the post-war construction period. However, on the basis of our face-
validation of the automatic identification algorithm, we conclude that the algorithm is fit for purpose and reliably identifies post-war neighbourhoods.

Figure 3. Comparison of a manual and automated generation of post-war neighbourhoods for the base set of assumptions (cf. Table 1)

Based on the automated identification of post-war neighbourhoods and considering our methodological uncertainty (cf. Table 1), we find that about 0.2 – 0.3 million people are living in very central neighbourhoods, 0.5 – 0.8 within central and 0.3 – 0.5 million in peripheral neighbourhoods in Switzerland. We thus notice a considerable spatial differentiation of the post-war neighbourhoods in terms of their geography, which allows for good prioritising with respect to sustainability implications. People living in very central areas with very high accessibility represent most interesting neighbourhoods for densification.

Figure 4 shows the relationship between the minimum population density and the densification potentials expressed as additional inhabitants which could be accommodated in post-war neighbourhoods. The percentage of densified post-war area expresses how much of the neighbourhood area has population densities below the minimum density value and would need to be densified to the respective density to realise the corresponding densification potentials. Figure 4a displays total potentials, Figure 4b distinguishes between different centrality classes.

We find that with increased centrality, current densities are higher and thus in order to accommodate additional inhabitants, neighbourhoods would need to be transformed to higher population densities. In case of densifying post-war neighbourhoods to minimum 200 population per hectare, which can be considered as dense for Switzerland, an additional 340,000 – 830,000 people could be accommodated, which corresponds to about 4 – 10% of the current Swiss population. Of this total densification potential, 34,000 – 78,000 people (≈10%) are in very central, 196,000 – 390,000 people (≈47 – 58%) in central and 113,000 – 362,000 people (≈33 – 43%) are located in peripheral neighbourhoods (cf. Figure 5). The use of the different sets of methodological assumptions for defining a neighbourhood is reflected in the notable uncertainty of our calculation results. However, the chosen parameters could be easily adapted. The methodological uncertainty mirrors the challenge of an automated and unambiguous identification of neighbourhoods.
Figure 4. Relationship between the minimum population density, the percentage of total post-war neighbourhood area which is densified to the minimum density and the resulting densification potential for a) all post-war neighbourhoods and for b) each centrality class.

4. Conclusion
In this paper, we propose a methodology for the spatial explicit assessment of sustainable densification potentials which can be up-scaled to the national scale. We focus on post-war neighbourhoods which are promising for sustainable densification and take into account a range of different constraints to add as much realism as possible to our assessment. The identification and geographic characterization of post-war neighbourhoods enables the quantification of densification potentials and spatial explicit planning of different densification strategies.

For Switzerland, our first estimate shows that the total population living in post-war neighbourhoods ranges in total between 1.1 – 1.6 million (13 – 19% of today’s population), depending on the methodological assumptions how neighbourhoods are identified. We find that within the urban context of Switzerland, considering the geographical location, not all locations are suitable to the same degree from a sustainability point of view. The post-war neighbourhoods of Switzerland could accommodate in total between 340,000 – 830,000 additional inhabitants, if neighbourhoods were transformed to a minimum density of 200 population per hectare, which can be considered as dense in a Swiss context. This potential corresponds to 4 – 10% of today’s Swiss population. Whereas only about 10% of this potential is located in very central locations, combined with central locations, this percentage increases above 50%.

We conclude that the presented methodology, which is grounded in the identification of post-war urban structural units, allows to effectively assess densification potentials and could form the basis for the study of broader densification implications at a national scale. Our methodology could for instance be extended to cluster post-war neighbourhoods into different archetypes for more in-depth architectural
and urban design densification analysis or for the assessment of densification implications with respect to further sustainability criteria such as energy, costs or emissions.

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References
[1] United Nations 2019 The sustainable development goals report 2019 (New York)
[2] OECD 2018 Rethinking Urban Sprawl (Paris)
[3] Conticelli E, Proli S and Tondelli S 2017 Integrating energy efficiency and urban densification policies: Two Italian case studies Energy Build. 155 308–23
[4] Präsidialdepartement Basel-Stadt 2015 Was ist eigentlich Verdichtung? (Basel, Switzerland)
[5] Stieß I, Umbach-Daniel A and Fischer C 2019 Smart small living? Social innovations for saving energy in senior citizens’ households by reducing living space Energy Policy 133 110906
[6] ILG 2012 Verdichtung der städtischen Wohnbevölkerung (Zürich, Switzerland)
[7] Swiss Confederation 2019 Federal Act on Spatial Planning
[8] Cabrera-Jara N, Orellana D and Hermida M A 2017 Assessing sustainable urban densification using geographic information systems Int. J. Sustain. Build. Technol. Urban Dev. 8 237–43
[9] ARE 2019 Verkehrerschliessung in der Schweiz
[10] BFS 2017 Eidgenössisches Gebäude- und Wohnungsregister
[11] BFS 2014 Räumliche Typologien: Der Raum mit städtischem Charakter
[12] Swissstopo 2019 swissBuildings3D 1.0
[13] Meinel G and Burgdorf M 2008 Automatische Ableitung von stadstrukturellen Grundlagendaten und Integration in einem geographischen Informationssystem (Berlin)
[14] Wickop E 1998 Environmental quality targets for urban structural units in Leipzig with a view to sustainable urban development Breuste, J., Feldmann, H., Uhlmann, O. (Eds.), Urban Ecology. Springer, Berlin, Germany. (Berlin, Heidelberg: Springer Berlin)
[15] Stokes E C and Seto K C 2019 Characterizing and measuring urban landscapes for sustainability Environ. Res. Lett. 14 045002
[16] Bobkova E, Berghauser Pont M and Marcus I. 2019 Towards analytical typologies of plot systems: Quantitative profile of five European cities Environ. Plan. B Urban Anal. City Sci. 0 1–17
[17] Lüscher P, Weibel R and Burghardt D 2009 Integrating ontological modelling and Bayesian inference for pattern classification in topographic vector data Comput. Environ. Urban Syst. 33 363–74
[18] de Smet F and Teller J 2016 Characterising the Morphology of Suburban Settlements: A Method Based on a Semi-automatic Classification of Building Clusters Landsc. Res. 41 113–30
[19] ARE Kanton Zürich; 2015 Leitfaden Dichtevorgaben umsetzen (Zürich, Switzerland)
[20] Domschy A, Kurath S, Mühlebach S and Primas U 2018 Stadtlandschaften verdichten: Strategien zur Erneuerung des baukulturellen Erbes der Nachkriegszeit ed Institut Urban Landscape ZHAW (Zürich, Switzerland: Triest Verlag)