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Updating digital elevation models via change detection and fusion of human and remote sensor data in urban environments

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## **Abstract**

OpenStreetMap (OSM) currently represents the most popular project of Volunteered Geographic Information (VGI): geodata is collected by common people and made available for public use. Airborne Laser Scanning (ALS) enables the acquisition of high resolution digital elevation models that are used for many applications. This study combines the advantages of both ALS and OSM, offering a promising new approach that enhances data quality and allows change detection: the mainly up-to-date 2D data of OSM can be combined with the high-resolution – but rarely updated – elevation information provided by ALS. This case study investigates building objects of OSM and ALS data of the city of Bregenz, Austria. Data quality of OSM is discerned by the comparison of building footprints using different true positive definitions (e.g. overlapping area). High quality of OSM data is revealed, yet also limitations of each method with respect to heterogeneous regions and building outlines are identified. For the first time, an up-to-date Digital Surface Model (DSM) combining 2D OSM and ALS data is achieved. A multitude of applications such as flood simulations and solar potential assessments can directly benefit from this data combination since their value and reliability strongly depend on up-to-date DSM.

**Keywords:** OpenStreetMap; Airborne Laser Scanning; change detection; 3D modelling, up-to-date Digital Surface Models

## 1. Introduction

Current developments of Web 2.0 and mobile devices, with which users can easily add geographic data to platforms like OpenStreetMap (OSM), create a new kind of dataset: up-to-date ‘human sensor data’ or crowdsourced geospatial data (Goodchild 2007a). Moreover, new technologies of ‘remote sensors’, e.g. Airborne Laser Scanning (ALS), also referred to as airborne LiDAR, provide highly detailed 3D topographic mapping. It is assumed that a combination of these two different kinds of sensor data results in a dataset that comprises specific benefits of both datasets and levels out the respective limitation. Hence, various applications, for instance urban planning, flood simulations, disaster management and solar potential calculations, could be improved by such a data combination leading to an up-to-date digital elevation model. For example, the existence of buildings in specific areas is essential for reliable results derived from digital elevation models (Jochem et al. 2009; Höfle & Rutzinger 2011).

One useful characteristic of Volunteered Geographic Information (VGI) such as OSM is that anybody can add and edit information at any time, which has the potential to generate very up-to-date datasets. Moreover, these datasets are extraordinarily rich because the source data provides a variety of attributes, geometries and semantic data. However, data is often-times only available in 2D and data quality tends to be spatially heterogeneous (Neis et al. 2012). In recent years, the scientific acceptance of crowdsourced data has increased significantly. More and more studies are being carried out in order to discern the quality of user-generated content and to identify its applicability to further projects instead of commercial data (e.g. Haklay 2010; Zielstra & Zipf 2010; Neis et al. 2012). The exploitation of the third dimension for outdoor environments using OSM and freely available digital terrain models has already been proven for web-based 3D visualization of OSM-3D (Over et al. 2010). Fur-

thermore, 3D indoor routing or 3D indoor evacuation plans can be created from OSM (Goetz 2012; Goetz & Zipf 2012a).

In contrast, the quality of ALS data is predictable because it is acquired via technical devices. Furthermore, laser scanning leads to the possibility of gaining 3D point clouds for multiple applications (Vosselman & Maas 2010). Yet, the high costs of ALS campaigns prevent regular scans, resulting in obsolete data.

Consequently, the combination of OSM as well as ALS data leads to an up-to-date dataset and additional information of features from each initial data source. Furthermore, the 3D information of ALS could be implemented in OSM data to generate OSM 3D city models while the 2D information of OSM could be used as a priori knowledge for automatic ALS-based object extraction (e.g. trees in urban areas; Höfle et al. 2012) as well as updating ALS data. Approaches using ALS data only for updating already exist such as the approach of Richter & Döllner (2010) who apply a method to compare heights of points of new ALS campaigns to heights in a recent 3D city model of former ALS campaigns. However, using ALS to update existing 3D city models cannot be as low priced and up-to-date as the fusion of ALS and OSM data presented here. Furthermore, OSM data can be accessed for free at any time (e.g. Geofabrik 2013) and there is also an increasing number of web portals providing ALS data (e.g. Opentopography 2013).

This paper analyses different key features of human and remote sensor data using OSM buildings and ALS to provide for a promising method in order to gain an up-to-date DSM. In this way a new ALS campaign might not be required for a number of applications. Official cadastre data is used as important reference for evaluating the quality of OSM data. The study region is located in Bregenz, a city with about 30,000 inhabitants in Vorarlberg, Austria, since a large ALS dataset of this region and the city already exists, providing a variety of urban landscapes.

Initially, an overview identifies individual characteristics of OSM and ALS data. Further, the potential of OSM data is evaluated by a comparison of building footprints using different true positive definitions in order to identify matches between the datasets. Moreover, the analysis of the city development between the ALS campaign in 2003 and the current data of OSM in 2012 displays parts of the city in which updating with OSM data is highly recommended. After this change detection, the up-to-date OSM data is used to complement the ALS dataset. The results of this case study clearly show the potential of fusing different sensor types for updating digital elevation models in urban areas.

## **2. Background**

### ***2.1 Human sensors, OpenStreetMap and quality evaluation***

People use web platforms more and more often not only to gather information but also to add their own information or edit content of others, e.g. in blogs or wikis. The term Web 2.0 is commonly used to describe this development (O'Reilly 2005; Goodchild 2007a). Michael Goodchild labelled this new data User-Generated Content (UGC); in the field of Geography he introduced the term “Volunteered Geographic Information” (Goodchild 2007a). Easy-to-use technical devices and new technologies enable people to acquire data and implement their individual experience and “knowledge about the surface of the Earth and its properties” in such platforms (Goodchild 2007b, 26). OSM can be considered as the most popular VGI project and the significant increase and common acceptance of such projects symbolise the immense potential of crowdsourced data. The general public can use device technologies like Global Positioning System (GPS) devices to capture geographic information such as coordinates. Additionally, they can take advantage of aerial images (e.g. Bing maps). In this way, features (e.g. buildings or streets) can be digitized on the screen, uploaded and compiled into composite digital maps (Goodchild 2007a). Furthermore, citizen science can be regarded as a

form of people as sensors (Resch 2013). People share measurements from everyday environments using their local and personal experience (Tulloch 2008).

The project OpenStreetMap was launched in 2004, and ever since, available data, the number of contributors and tools to extract data from OSM have been growing (OpenStreetMap Wiki 2013a). Further studies showed that around 150 new members have registered on OSM every day since 2011 (Neis & Zipf 2012). A closer look at the contributors' activity reveals similarities to other online communities with regard to participation inequalities. Hence, only 38% of the contributors made at least one edit and just about 5% of the registered members contributed to the OSM database in a more productive way (Neis & Zipf 2012). In order to evaluate this data scientifically, research needs to find out standards and measurements of quality for these data and their additional information, for instance attributes such as street or place names (Goetz & Zipf 2012b). The quality of OSM can also be evaluated by the comparison to reference data. Neis et al. (2012) used the street network of Germany from the commercial data provider TomTom and in the same way Ludwig et al. (2010) used the Navteq data of Germany as reference. Yet, studies were not only performed for Germany but also for England (Ather 2009; Haklay 2010), France (Girres & Touya 2010), Greece (Kounadi 2009) and the USA (Zielstra & Hochmair 2011). In addition to these studies based on comparisons, the quality of OSM can also be evaluated with regard to its applicability (Mondzech & Sester 2011; Mooney et al. 2012). Using the OSM project as an example, Mooney & Corcoran (2014) investigated the characteristics and role of integrating VGI in Digital Earth applications on a global scale.

## ***2.2 Airborne Laser Scanning (ALS)***

Laser Scanning is widely used in case studies in a multitude of research initiatives as well as for 3D topographic mapping of large areas by national mapping agencies. Even with vegetation and clouds, high-resolution area-wide measurements of 3D elevation can be determined

(Vosselman & Maas 2010). A laser beam is used to identify the distance between the measuring device and the reflecting surface on the ground. Furthermore, the strength of the reflected beam can be evaluated in order to identify the target surface itself (Höfle & Pfeifer 2007). There are three distinct modes of carrying out the scans: from airborne (plane, helicopter), mobile (car, boat) or static terrestrial platforms. The analyses of this paper are based on data derived from the airborne case.

ALS can be used in different ways. On the one hand, the 3D point cloud is directly used for digital elevation models such as a Digital Surface Model (DSM). All laser points are rasterized into a regular grid, where the cell value represents the maximum elevation. However, this transformation into raster leads to a loss of information compared to the 3D nature of the point cloud. On the other hand, terrain point measurements (e.g. of the bare Earth) for the generation of a Digital Terrain Model (DTM) even in densely forested areas are made possible. The relative heights above the terrain are represented in a normalized DSM (nDSM), which is calculated by subtracting the DTM from the DSM (Höfle & Rutzinger 2011).

There are various advantages of the ALS system, especially in areas where surfaces have little or even no texture so that image matching and manual measurements deliver insufficient results. However, ALS data has the disadvantages of high costs for campaigns with only small coverage in comparison to other remote sensing techniques (Kraus & Pfeifer 1998). Yet, there are many more advantages such as a variety of algorithms to automate distinct calculations with raster data derived from ALS. Further, a software for point cloud processing such as OPALS (Orientation and Processing of Airborne Laser Scanning data) can be applied so that the full accuracy and different attributes can be used for point cloud classification, georeferencing and city modelling, for example (Mandlbauer et al. 2009).

### 3. Study area and datasets

The study area of Bregenz is a city with around 30,000 inhabitants and is located close to Lake Constance at the border between Austria, Germany and Switzerland. There are heterogeneous buildings such as terraced houses in the old town as well as semi-detached and detached houses in residential areas.

#### 3.1 *OpenStreetMap data*

OSM data can be extracted online from Geofabrik (Geofabrik 2013). Different features can be downloaded such as streets, land use or buildings. The latter one is chosen for this study where only building footprints are investigated.

Quality of OSM mainly depends on the contributor, both on his accuracy and his experience (Haklay 2010). In general, the more mappers that are active in an area, the better the quality is supposed to be. Moreover, some analyses resulted in higher coverage of data in urban areas (Zielstra & Zipf 2010; Roick et al. 2011a; Neis & Zipf 2012; Hecht et al. 2013). However, Neis et al. (2013) expanded the quality evaluation to selected regions all over the world and showed that further factors such as income can also influence the results. Therefore, it is not possible to make a universal statement about data coverage regarding urban or rural areas. Furthermore, the study by Arsanjani et al. (2014) had a closer look at the spatio-temporal development of OSM contributions. For the specific situation of the city of Heidelberg, their prediction using cellular automata revealed that the density of contributions is linked to a certain urban land use type.

Not only can a comparison of OSM and reference data be used to describe the current OSM dataset, but also historical information of OSM itself. Thus, Barron et al. (2014) developed a means of gaining parameters in an intrinsic way that can be used as indicators for quality assessment. The intrinsic OSM analyzer (iOSMANalyzer) framework enables conclusions to be drawn among others, about mapping behaviour, polygons, data input, edits and how up-



to-date the data is. The tool is applied to the OSM-Full-History-Dump (OpenStreetMap Wiki 2013b) for the city of Bregenz the calculations and figures show that there was a strong increase of polygons in June 2011 (Figure 1).

*Place Figure 1 around here*

Though, a closer look at the attributes of historical information shows that about 3,700 features, mostly building polygons, were solely added by one OSM contributor. This was exactly at the time when the new images of GeoImage.at were made available to the OSM project for tracing geographic features with 4 pixels per square meter instead of former images with 1 pixel per square meter (OpenStreetMap Wiki 2012b). Further, the comparison to the cadastre data reveals high completeness of buildings per se and correctness regarding the accuracy of the building outline. Very often a high number of new created objects within a short period of time hints at a bulk data import. Though, in this case it is different according to the results of the iOSMAalyzer (Figure 2): The analysis of changesets, attributes (source-tags) and user profiles revealed that the buildings were digitized by one single mapper.

*Place Figure 2 around here*

Moreover, about 80% of the data was edited less than 12 months ago (Figure 3) so that the information of the OSM history is useful for deciding on the benefit of OSM data for a fusion with other datasets. Therefore, the approach might be very efficient in the identification of areas with inadequate quality and for a pre-selection of appropriate datasets for optimal results of a combination of datasets.

*Place Figure 3 around here*

### ***3.2 Airborne laser scanning data***

An ALS campaign launched by the Land Surveying and Geo-Information Office of Feldkirch in 2004 (TopScan 2004) resulted in a rich ALS dataset. For the Vorarlberg region a spatial resolution of DSM and DTM from ALS of 1 m is available. This analysis uses the nDSM, in which relative heights of buildings are indicated, providing a dataset for comparisons between buildings without any influence of the terrain height (Höfle & Rutzinger 2011). Additionally, the federal state of Vorarlberg provides new orthophotos of the year 2009. They are used as a base map as well as illustration for the comparison of ALS and OSM data. Figure 4 shows a comparison of the data used for this study.

*Place Figure 4 around here (in colour only for online version)*

## **4. Methods**

This section first describes preparatory work which reveals the need for the application of merging of building footprints to derive adequate results. Thereafter, the cadastre data which is used for comparison as well as an overview of possible relationships between feature objects is illustrated. Moreover, the methods of comparison and combination as well as the concepts of completeness and correctness for the evaluation of the results are depicted.

### ***4.1 Merging of building polygons***

OSM volunteers usually digitize building polygons using aerial images or walk around buildings with a GPS device. High-resolution aerial images allow not only the identification of roof planes but also of more precise sub-structures such as terraced, semi-detached or de-

tached houses. Yet, it is more comfortable for mappers to simply tag it as building in general (building=yes). Thus, most OSM building polygons represent a block of buildings rather than single buildings due to their official borders as in cadastre polygons. Accordingly, there are many n:1 relations, i.e. several cadastre polygons are represented by one OSM polygon (Hecht et al. 2013). These difficulties with matching the appropriate polygon can be overcome by merging neighbouring polygons. In this way, the different representations of objects in cadastre, OSM and ALS are taken into account and the highly segmented cadastre polygons are turned into blocks of buildings, which makes a comparison more representative, especially concerning the number of buildings because the area is mostly represented correctly.

Similarly to the OSM footprints, the specific heights of the nDSM, that indicate building areas, also display the outlines of the roofs as the highest surface elevation rather than the official building borders (i.e. walls) as in semi-detached or terraced houses in cadastre data. That is why merging is applied for the quality assessment of the OSM data according to the similarities to the building representation in ALS data.

The change from many small areas to rather few large areas in cadastre is illustrated in two diagrams (Figure 5 and 6). Figure 6 also shows the geometric changes of the merging process. The number of polygons of the different datasets is adjusted for more realistic matching. The contrast of areas from OSM and cadastre is visible, too. In the study area, OSM has 3832 polygons and the cadastre 5077. After merging, the OSM data has 3309 and the cadastre data 3839 polygons.

*Place Figure 5 around here*

*Place Figure 6 around here (in colour only for online version)*

## 4.2 Comparison

The accurate cadastre data of the city administration is chosen as reference data for an appropriate comparison. There are various types of relationships between feature objects in the two datasets. This is based on different methods of data acquisition: cadastre data by a survey of land and official boundaries for proprietary building footprints and, on the other hand, OSM building polygons digitized from aerial images and users with their GPS devices. There are different possibilities of relations and if there are multiple features, “m” is used for cadastre and “n” for OSM polygons (Table 1).

*Place Table 1 around here*

On the one hand, the area and number of objects can be summed up and compared to cells of a raster of the reference data. However, very often buildings such as garages or small sheds are added in OSM while there is no corresponding object in cadastre. Hence, the number of buildings and building footprint area varies strongly even if there might be a good representation of the “real” buildings. Further, new buildings already added in OSM might not have a corresponding polygon in cadastre which leads to a deviation in the percentage of accuracy although the accuracy cannot be applied on buildings that do not exist.

On the other hand, the object-based approach uses polygons of buildings which can be compared concerning their shape, number and area in comparison to the polygons of the reference data (Mooney et al. 2010a, 2010b; Hecht et al. 2013). This enables the accuracy of selected features to be calculated in relation to their representative in the other dataset instead of a whole area. There are two distinct options of using the area of polygons. Firstly, the overall area of all buildings can be used, which leads to a generalized result. Secondly, the comparison can be based on a morphological analysis of the building footprints (Hecht et al. 2013; Fan et al. 2014). The following analysis will focus on the object-based approach using the

overall area option in the case of the centroid method and the morphological analysis applying the overlap method.

Furthermore, to ensure data interoperability, guidelines and standards are required. Therefore, the quality principles of ISO 19113 can be applied (Kresse & Fadaie 2004; Van Oort 2006; Haklay 2010; Koukoletsos et al. 2012). The importance of such principles can be seen in new developments such as the ISO/FDIS 19157 on geographic information, in particular data quality, combining ISO 19113, ISO 19114 and ISO/TS 19138 (ISO 2013). Especially, the calculation of correctness or positional accuracy in the words of Haklay (2010) is important for the OSM data due to the fact that volunteers might neither have coherent collection standards nor professional mapping background. Yet, the common assumption of a majority of GIS amateurs contributing to VGI projects can be disproved. A survey by Lechner (2011) showed that 50% of the respondents regard their profession as related to computer science. In another one carried out by Budhathoki (2010) 50% of the participants claimed to have some sort of GIS background. These results illustrate the high proficiency of OSM contributors regarding their computer skills and geographical knowledge.

Further, it is highly recommended to assess completeness in order to check the coverage of data collection. Members of VGI projects might add buildings according to their own estimation of importance, which leads to fragmentation of data and lack of systematic coverage. Of course this issue will always be part of OSM data due to its characteristics as a VGI project; however, analyses can reveal which areas are suitable for further studies and parts that should not be used or only with constraints (Haklay 2010). All in all, those two aspects are essential to establish accurate evaluation of the quality of the studied OSM data as well as to conclude predictions about the benefits of a fusion.

A confusion matrix exemplifies the assessment of True Positives, False Positives, True Negatives and False Negatives. First of all, True Positives (TPs) need to be identified.

They are the classified objects (OSM) that have corresponding reference objects (cadastre) in contrast to False Negatives (FNs) which are those objects of the reference that have no matching classified object. Further, False Positives (FPs) are classified objects with no equivalent reference object. If there is no object in both datasets, it is a True Negative (TN), which will not be considered in this work (Rutzinger et al. 2009). We use the following equations to derive completeness and correctness (cf. Rutzinger et al. 2009):

$$\text{Completeness} = TP / \text{number of reference objects} \quad (1)$$

$$\text{Correctness} = TP / \text{number of classified objects} \quad (2)$$

### **4.3 Centroid method**

In the case of an area object, a centroid is defined as the “artificial point reference, which is located so as to provide a summary measure of the location of the object” (Longley 2011, 102). Bartelme (2005) defines the centroid as the geometric centre of gravity, which contains the information of the polygon. Yet, in both cases, the centroid might be located outside of the building polygon (e.g. for L-shaped buildings). Therefore, the centroids for this comparison are calculated by applying an “inside” option, guaranteeing that the centroid lies inside the polygon. Afterwards, it can be checked whether this polygon lies inside a corresponding polygon, respectively. In the case of the building polygons this might indicate that the centroid of one building lies in the polygon of the other and thus, it is the representation of the same building.

Aiming at identifying the buildings in OSM that have a respective building in cadastre, OSM polygons that include a cadastre centroid represent the TPs and are therefore selected. By joining this selection to the original file the distribution of TPs and FPs in Bregenz is

visible. In this way, the correctness of the OSM footprints as well as their completeness in regard to the reference data can be evaluated.

The same method is applied for the cadastre polygons using the OSM centroids as selecting feature. In this way it can be revealed in what numbers the OSM buildings represent the cadastre data. This method would be a means of identifying relationships between cadastre and OSM because there are many n:m relationships. However, merging mostly leads to 1:m relations and therefore predictions about the OSM buildings are difficult to make. Thus, the following discussion focuses on the previous approach with cadastre centroids and OSM polygons, which is also more appropriate for the quality assessment of OSM data.

The improvement of data quality by a fusion only needs to be applied if there is a change in the data, e.g. new or demolished buildings. Hence, the cadastre of 2003 when the laser scanning was done and the cadastre of 2012 – the most recent one – are compared using the method of centroids illustrated above. This will enable the identification of changes over time and the justification of the developed fusion method.

#### ***4.4 Overlap method***

In contrast to the centroid method, where a polygon is compared to a point, the overlap method uses two polygons. The “relative area overlap is defined as the ratio of the area of intersection, to the area of union” (Maruca & Jacquez 2002, 72). In this analysis, the comparison of OSM data to the cadastre reference discerns the quality of OSM. Thus, the area of the OSM building polygon is used instead of the union area, which would be the combined area of cadastre and OSM building polygons. In order to find out whether a polygon of OSM is represented in the reference data and vice versa a threshold needs to be applied. If the overlap area has 30% or less of the OSM polygon area, it might be caused by neighbouring buildings. Consequently, higher thresholds such as 50% are required (Rutzinger et al. 2009). The follow-

ing analysis uses different categories of overlap percentages to classify the data (50% and 80%).

#### ***4.5 Fusion of OSM and ALS***

In order to combine advantages of both ALS and OSM data, a straightforward approach of fusing an OSM building raster with an ALS raster, is developed. The main idea is to take the OSM polygons as a mask to extract the nDSM values of existent ALS buildings and to integrate a new fixed building height into the nDSM where no building is present in the laser data. Cells in the nDSM outside the OSM building mask are set to zero height.

As a first step, the mean nDSM height values per OSM polygons are calculated and joined to the OSM vector layer. On the basis of these values, buildings which are new in OSM (nDSM mean height  $< 2$  m) and those which already exist in OSM ( $\geq 2$  m) can be detected, respectively. The threshold level for selecting an area as building is set to 2 m according to the definition of Höfle et al. (2009). All the areas of polygons with mean heights under the threshold indicate that there is a building in OSM but not in the nDSM due to the missing height above ground.

Due to the different building boundaries of ALS and OSM, a buffer of 2m is applied to the layer with the already existing polygons. These two vector layers are rasterized according to the nDSM raster extent and resolution.

The fusion of the ALS and OSM rasters is based on different conditions: If there is a new OSM polygon, the most frequent mean building height value per nDSM of the study area is used as fixed building height for the fusion. Additionally, the new height value can also be gained from the OSM building attributes which might include the building height. Yet, this data is very rare because generally only about 0.5% of the buildings are tagged appropriately and therefore fix height values and random deviation are mostly used (OpenStreetMap Wiki



2012a; Goetz & Zipf 2012b). The analysis of the tags of the study area reveals even a lower value: just 0.06% of the buildings have information on their height.

As a next step, if there is a building in OSM that also exists in the nDSM, the original height values of the nDSM cells are used. For all building values of the nDSM that do not appear in the OSM dataset anymore the value is set to 0 m. In this way the demolished buildings are removed. A minor disadvantage can be seen in the fact that vegetation might be detected as height, i.e. a large tree was standing where now a new building present, and is therefore implemented. Yet, this problem could be easily overcome by prior building detection in the ALS dataset (cf. Kaartinen et al. 2005).

## **5. Results and discussion**

### ***5.1 Centroid method***

Focus is set on the TPs and FPs of OSM building polygons with a cadastre centroid because they can be used to reveal the quality of OSM. The results of the entire city can be displayed in a map with a grid with the cell size of 100 m by 100 m, in which the accumulated TPs are shown (Figure 7). Both, the absolute number of polygons (hatching) and the average value of TPs (percentage) of all buildings per grid cell are indicated.

*Place Figure 7 around here (in colour)*

Thus, in contrast to the average values for the area of Bregenz, the grid map of the same extent identifies specific regions with their inherent characteristics enabling appropriate evaluations of the calculations. In the old town, only a true positive rate of 25-50% with an average number of about 5-9 polygons per grid cell is displayed. However, the old town has many more buildings and the OSM quality is definitely underestimated. The problem can be seen in the merging process. Due to the building blocks it is necessary to merge the cadastre

data because every single building outline of official data is indicated. In contrast, the OSM borders are digitized predominantly by using aerial images and roof outlines; consequently, only building complexes are indicated which leads to a strong inequality of  $m:n$  and  $m:1$  relations. However, not all OSM buildings are adjoining and thus after merging, there are more buildings in OSM than in the cadastre data. Hence, there are many  $1:n$  relations and accordingly the TP rate is rather low. Additionally, the merging results in a reduction of the number of polygons in this area. In summary, the centroid method tends to result in an underestimation of OSM quality and a shift of number of polygons.

Secondly, a special case occurs for the housing estate “Achsiedlung” next to the river Bregenzer Ach (see Figure 7). Several buildings are connected to each other. However, the merged OSM outlines are mostly separated whereas the merged cadastre polygons are represented in one large building complex. This leads to a  $1:n$  relationship and the application of the centroid method results in just one cadastre centroid. Hence only one of the several OSM building polygons can be identified as TP and the representation of OSM data cannot be assessed appropriately with this method in this area and results in a true positive rate of 0-25%. Without merging, these buildings are considered as single houses as in the case of detached houses. Therefore, a matching and quality assessment in this specific housing area with OSM polygons and cadastre centroids is more realistic without merging.

In contrast to the problems that occur with merging in the previous two cases, semi-detached houses are turned into one polygon by the application of merging; consequently, they have the same outline as OSM polygons. Thus,  $m:1$  relationships can be turned into  $1:1$  and the OSM quality can be assessed more appropriately. Most realistic results for the assessment of OSM quality are gained with the centroid method in the case of detached houses in residential areas. There are  $1:1$  relationships and therefrom the TPs are identified and the number of polygons to evaluate the relative percentage can be considered as appropriate.

It is necessary for the centroid method to merge the data in order to overcome the major problems with the unbalanced m:n and many m:1 relations. However, the merging itself brings about disadvantages with various 1:n relations. Thus, the centroid method results in underestimated values of the OSM quality for areas with terraced houses and building complexes. Yet, in residential areas with semi-detached and detached houses the method yields highly realistic results. Consequently, the choice of method needs to be applied to the characteristics of the study area.

### ***5.2 Overlap method***

The percentage of the overlap area in relation to the original area can be categorized using thresholds of 50% and 80%. The overlap area can be compared to the cadastre polygons and to those of OSM, respectively. Focus is set on the latter one because similarly to the centroid method, the usage of OSM buildings as the basis of comparison is more appropriate to evaluate the quality of OSM than the usage of the cadastre. Therefore, as an example, the overlap area of cadastre and OSM is compared to the OSM area and the results for not merged and merged data are shown as an average for the whole city of Bregenz (Table 2).

*Place Table 2 around here*

Regarding the results of the comparison to the OSM data, the data without merging reveals numerous m:n or m:1 relations of cadastre to OSM. Therefore, the correctness and completeness especially in number is significantly lower than with merged data. In the case of the TPs with more than 80% overlap, there is an increase of correctness of area of 13% and of completeness of area of 14% after applying the merging.

Additionally, the method causes lower values in correctness and completeness for area than for number of objects, which stands in contrast to the centroid method. Only in the case of merged data with an overlap greater than 80% the correctness and completeness of area is higher than those of counted objects. This aspect can be explained by the intersection of the two datasets into several small parts. Thus, the overlap area tends to be a part of the base polygon and the number is counted. However, the overlap is relatively small and that is why the correctness and completeness of the area has low percentage values.

Concerning the area with an overlap greater than 80%, it is obvious that there are higher values in correctness and completeness than in numbers due to the fact that the merging leads to many 1:m relations. Thus, numerous OSM polygons intersect with a single cadastre polygon and create larger overlap areas. Therefore, the average of percentages shifts to higher values after merging.

Correctness and completeness of number is highest at around 50-80% and decreases again after 80%. Regarding correctness and completeness of numbers of single building polygons this shows that the overlap method is in contrast to the centroid method not as appropriate for assessing the quality of OSM. However, the correctness and completeness of the area itself is indicating realistic values of the quality assessment due to an increase towards 80% to 100%.

In opposition to the centroid method, the quality evaluation with the overlap method of the OSM data in the old town is fairly realistic because there is mostly an overlap between 80% and 100%. Only, residential areas with detached houses reveal lower percentages of overlap between 50% and 80% (Figure 8). This may be caused by differences in building outlines due to the diverse dataset. OSM polygons tend to have larger outlines due to the roof overhangs. Furthermore, mappers may not be as accurate as the technical acquisition of cadastre data and therefore outlines are shifted. Thus, the overlap area decreases. All in all, the re-

sults of correctness and completeness of the overlap method demonstrate the applicability for areas with terraced houses and blocks of buildings. In contrast, problems occur in detached houses where 1:1 relationships are present and the dissimilarities in data acquisition become evident.

*Place Figure 8 around here (in colour only for online version)*

### ***5.3 Change detection in multitemporal building footprint data***

The comparison of the cadastre data in 2003 and 2012 using the centroids as illustrated above reveals significant changes. In 2003, there were 4830 building polygons whereas by 2012 the number has increased to 5077 resulting in an addition of 247 buildings. However, the numbers of buildings cannot indicate the changes because newly built and demolished buildings can compensate each other. Thus, there are many more changes to the city than just an increase of 247 buildings. To find out the correct number of changes the method of centroids can be applied. The centroids of the polygons are calculated and it is analysed in which polygons of 2012 centroids of 2003 can be found. The building polygons that have a corresponding centroid may be considered as buildings that are still there and the remaining ones might be newly built houses after 2003. The same can be applied for the polygons of 2003 and the centroids of 2012. The polygons of 2003 with a centroid of 2012 inside are buildings of 2012 that were already there in 2003. In contrast, the remaining ones are buildings that were there in 2003 but have been demolished by now.

With regard to the cadastre data 2012 and corresponding centroids of 2003, there are 4650 building polygons. Using the cadastre centroids of 2012 together with the cadastre polygons of 2003, the calculations reveal 4623 corresponding building polygons. Comparing the cadastre data of 2012 to 2003 shows that there are 8.8% (427) new buildings and 4.3% (207)

demolished buildings. Thus, an overall change of 13.1% is calculated for the study area of Bregenz.

#### ***5.4 Fusion of OSM and ALS***

A change detection using official cadastre data of 2003 and 2012 represents a more efficient way of comparison than using ALS and OSM data because, as mentioned above, the outlines of building polygons of ALS and OSM may differ according to their individual way of acquisition. Yet, the ALS data captures the buildings of 2003 and therefore resembles the cadastre of 2003. Additionally, the OSM data of 2012 is an adequate means for a fusion with the ALS data as illustrated by the above mentioned results of the quality assessment. Hence, the fusion of ALS and OSM is already justified by the change detection of the official cadastre data of 2003 and 2012.

Clearly indicated by the results of the change detection, the ALS data requires modifications and updates for large parts of the city area. Due to differences in data acquisition, the resulting polygons of the nDSM have heterogeneous height values because the outline of the OSM buildings might not correspond correctly to the detected heights of the ALS data. Moreover, the rasterizing of the point cloud needs to be considered because in the point cloud each point represents a specific height; yet, a grid such as the nDSM implies continuous data and each cell embodies a selected aggregated height value (e.g. average or maximum) of the points inside. In contrast, buildings are discrete objects with distinct boundaries. Figure 9 shows the shaded relief of the nDSM before and after the fusion. The implemented and removed buildings become clearly visible.

*Place Figure 9 around here*

## 6. Conclusion and outlook

The advantages of VGI such as being up-to-date and containing further information concerning geometry, attributes and semantic information stand in contrast to its spatially heterogeneous quality and the display mainly in 2D. However, the disadvantages can be compensated via data fusion: The ALS point cloud with its homogeneous and known data quality offers the possibility of 3D, for example. Thus, the high costs of new ALS campaigns can be reduced by continuous updates of the normalized DSM using the most recent OSM data for areas where high quality is expected. Consequently, after the fusion there will be a cost-efficient up-to-date dataset, additional information on features and 2D as well as 3D applications. For instance, the ALS can provide height information that can be implemented with OSM data in order to create 3D city models. On the other hand, new or demolished buildings as well as further attribute information from OSM data can be used to update the normalized DSM or the point cloud of ALS. The intrinsic approach of Barron et al. (2014) enables the assessment of relative quality indicators of OSM without the need of further data. Hence, required VGI data for a fusion with ALS can be assessed beforehand in order to evaluate the benefits in advance

Moreover, the comparative methods presented here, provide adequate means to discern the quality of the OSM building layer because they complement each other. The results of the centroid method in residential areas of Bregenz achieve very realistic values for completeness and correctness of OSM data. At the same time, this method underestimates the OSM quality in the old town, which signifies that areas with terraced houses might rather use the overlap method. In contrast, the overlap method reveals the opposite results. The merging method, which was estimated as a necessary application for adjusting relations between feature objects of different datasets, has strong influence on the results. Clearly, the methods need to be selected according to the requirements of the investigation. Furthermore, additional

techniques need to be investigated to evaluate the quality of OSM in order to enable the broad usage of these large datasets.

In regard to the combination of OSM and ALS, the methods depicted here work very well to identify newly built and demolished houses. A future, more refined approach might allow the detection of reconstructions of buildings which lead to a change in footprint and thus require modified methods.

Looking ahead towards an integral Digital Earth application (Mooney & Corcoran 2014), the described tools for quality assessment and fusion of OSM and ALS data might be implemented in a web service, too. There are already several approaches aiming to fuse different datasets that include OSM and reference data (Wiemann 2010). In such a web service of OSM and ALS data, changes could be detected automatically and 3D OSM city models as well as 3D ALS point clouds can be updated real-time or on demand.

Further information on features in OSM such as the height or the shape of a roof might be used for the ALS point cloud. Moreover, not only tendencies regarding the function of buildings and their relevance to the mapper but also the assumed relevance to the user of this service could be revealed. This might support predictions of areas and buildings that need to be updated or scanned more often due to low user activity; conversely it could be necessary to conduct a new laser scanning campaign in areas where rapid changes render existing OSM update unsatisfactory. Such ‘Location Based Sensing’ via crowdsourcing could become a means for future sensing activities.

To conclude, this paper identifies the benefits and challenges of methods for assessing quality in heterogeneous areas and illustrates some paths towards the combination of OSM and ALS data. The results show the high potential of data combination and clarify the excellent potential for future studies to contribute to these seminal approaches.



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**Table 1. Cardinalities of relationship between buildings of OSM and cadastre.**

Relationship	
1:1	The cadastre building has a corresponding OSM building.
1:0	There is only a building in the cadastre but nothing in OSM.
1: n	There are various buildings in OSM (n) corresponding to one cadastre building.
0:1	There is no building in the reference data that corresponds to an OSM building.
m:1	Several buildings of the cadastre (m) have only one corresponding OSM building.
m:n	There are several buildings in the cadastre (m) that correspond to various buildings in OSM (n).

**Table 2. Correctness (Corr.) and Completeness (Com.) of number (n) and area (a) with different thresholds of overlap (o) in OSM (upper part) and merged OSM (lower part).**

	not in cadastre [%]	0 % < o < 50%	50% =< o < 80%	80% =< o < 100%	o completely contained [%]	sum [%]
Corr. n [%]	4.49	22.34	39.93	33.12	0.13	100.00
Com. n [%]	3.39	16.86	30.14	25.00	0.10	75.48
Corr. a [%]	0.00	6.52	20.09	36.17	0.00	62.79
Com. a [%]	0.00	6.92	21.31	38.37	0.00	66.60
Corr. n [%]	4.56	8.73	45.54	40.98	0.18	100.00
Com. n [%]	3.93	7.53	39.26	35.32	0.16	86.19
Corr. a [%]	0.00	2.47	21.17	49.17	0.33	73.14
Com. a [%]	0.00	2.62	22.46	52.16	0.35	77.24

Figure 1. Strong increase of buildings in June/July 2011 (calculated with iOSMAnalyzer from Barron et al. 2014).

Figure 2. Strong increase of polygons that could be caused for instance by a data import, a bot correcting the imported data, a mapping party or a very active OSM community (calculated with iOSMAnalyzer from Barron et al. 2014).

Figure 3. All polygon features of April 2012. About 80% is less than one year old. High time-liness is visible (calculated with iOSMAnalyzer from Barron et al. 2014).

Figure 4. Section of Bregenz in (a) OSM map, (b) orthophoto and (c) nDSM derived from ALS. The height in the nDSM is displayed in greyscale (white = high, black = low). The comparison clarifies structures such as buildings.

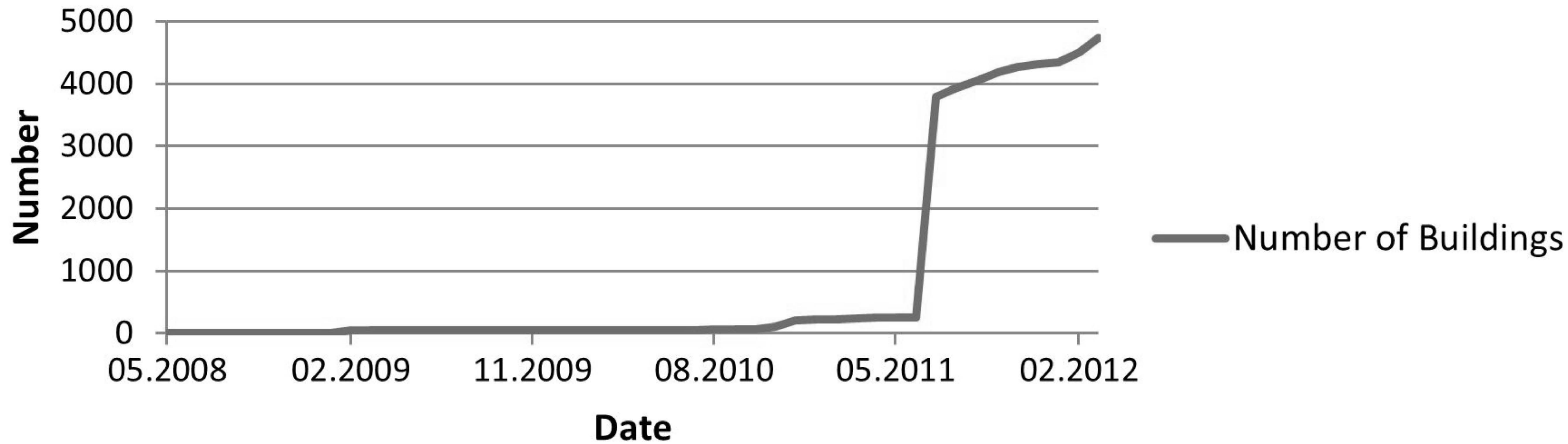
Figure 5. Cadastre and OSM polygons with the number of polygons according to a specific area (a) before and (b) after merging.

Figure 6. Polygons of cadastre and OSM data: Merging combines neighbouring polygons. (© OpenStreetMap and contributors; CC BY-SA; Cadastre © City of Bregenz).

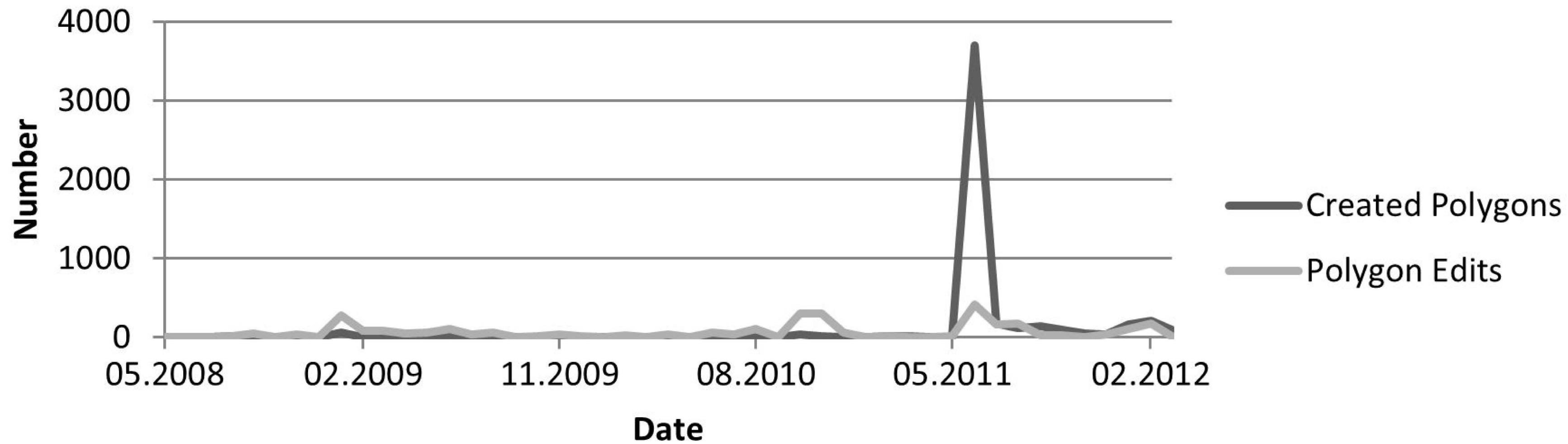
Figure 7. OSM polygons with centroids of cadastre in a grid with cell size of 100 m by 100 m. Colours indicate percentage of True Positives (i.e. OSM polygon has a centroid of cadastre inside) and the hatching specifies the number of polygons. Fields in grey: OSM polygon has no cadastre centroid inside (© OpenStreetMap and contributors, CC BY-SA; Cadastre © City of Bregenz).

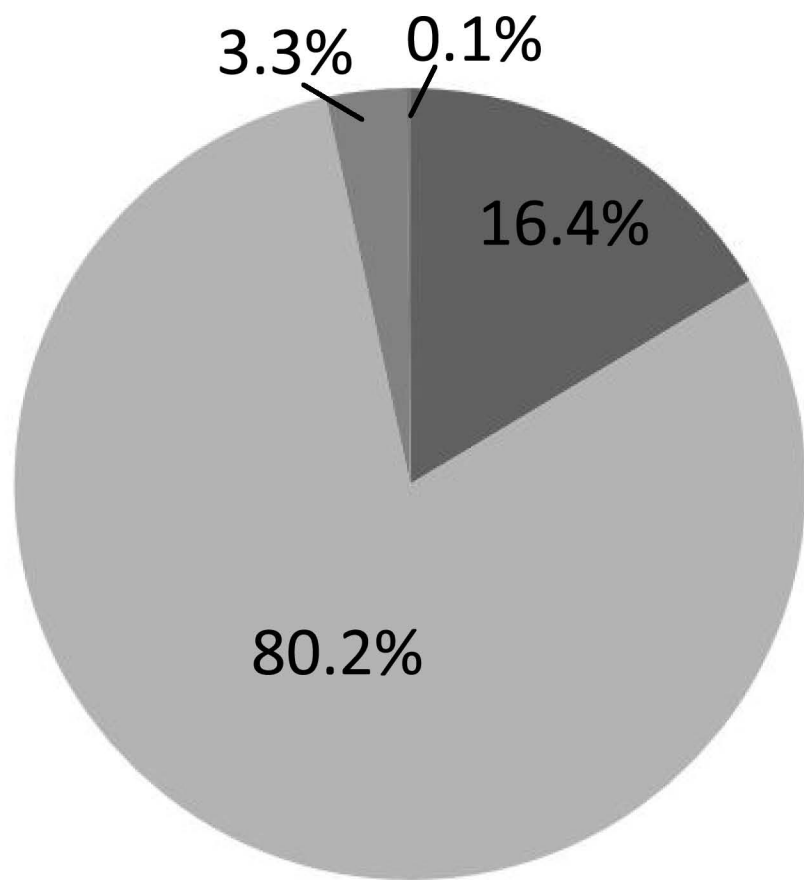
Figure 8. Map of Bregenz with coloured building polygons according to the percentage of share of the overlap (cadastre/OSM) in area of OSM polygons. (© OpenStreetMap and contributors, CC BY-SA; Cadastre © City of Bregenz).

Figure 9. Laser Scanning nDSM before (a, c) and after (b, d) fusion. Implemented (b) and removed (d) buildings can be identified. Fusion can also be used as vegetation filter (Geo-data © 2010 Federal state of Vorarlberg).









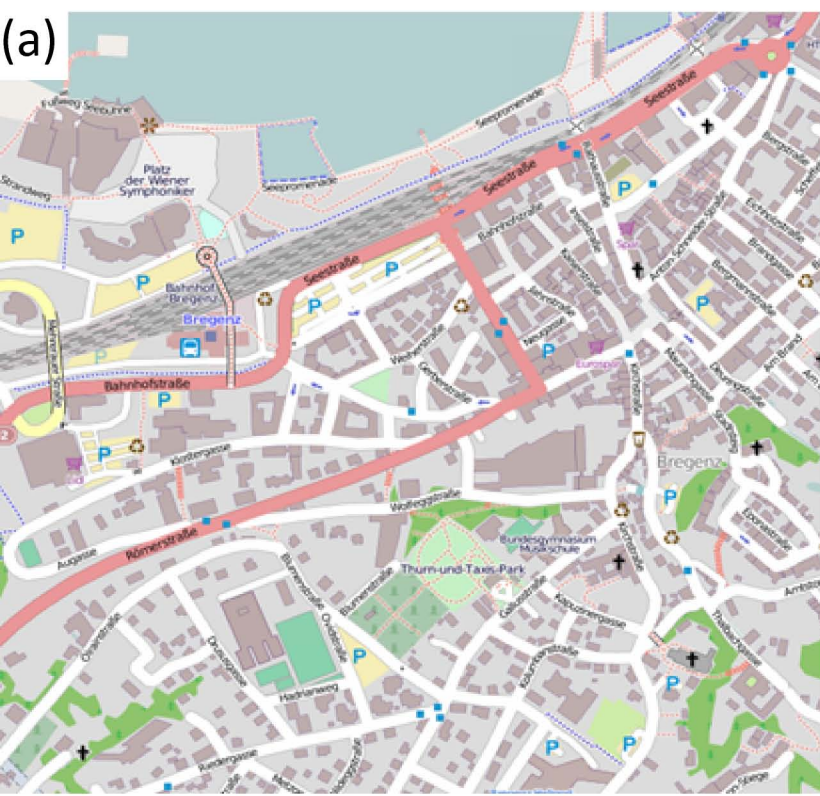
■ < 6 months

■ > 6 months and ≤ 1 year

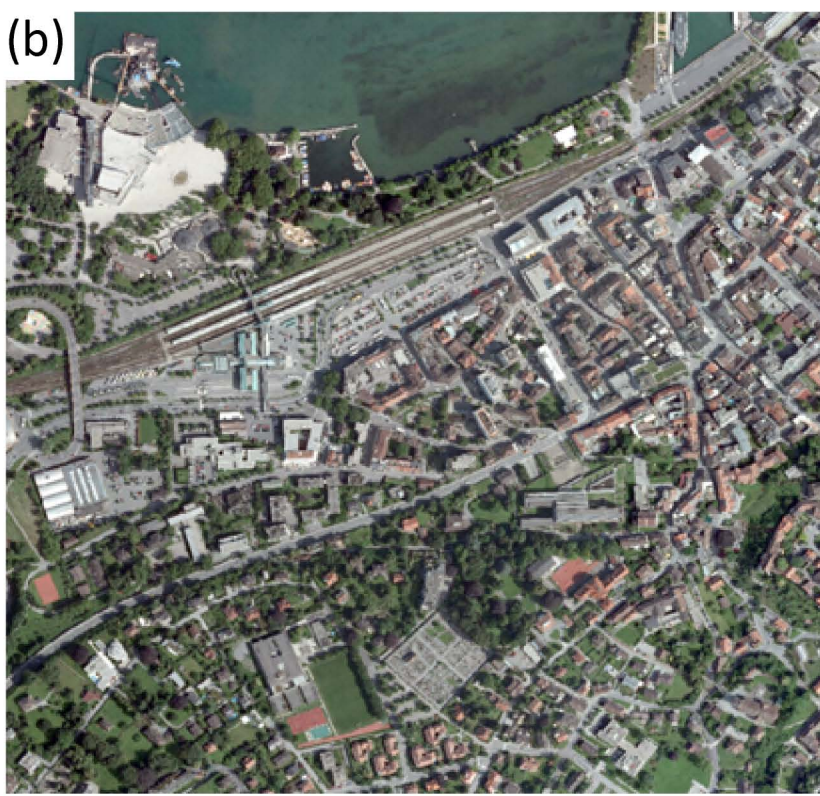
■ > 1 year and ≤ 2 years

■ > 2 years

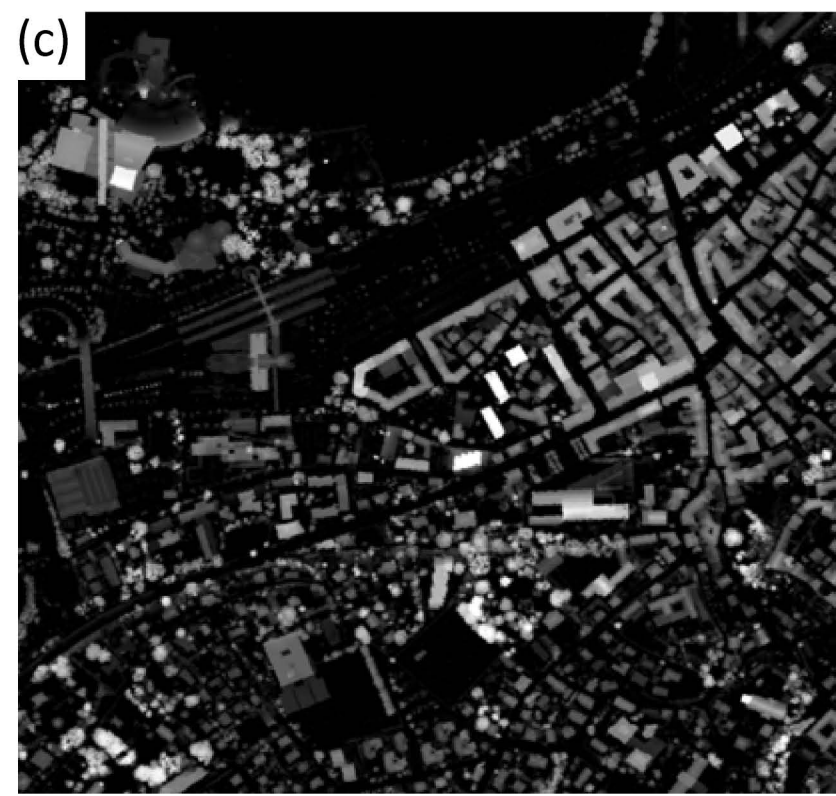
(a)



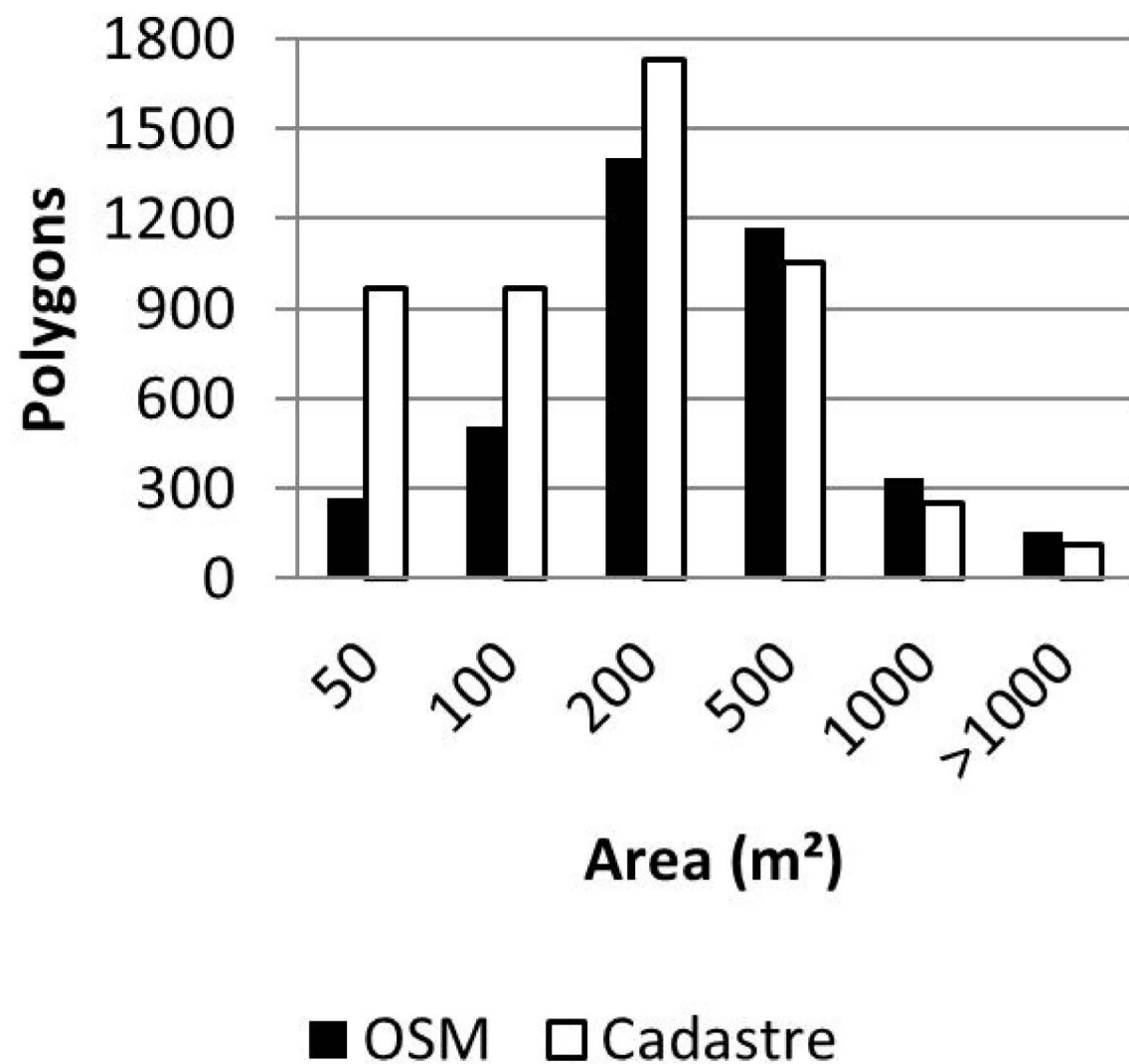
(b)



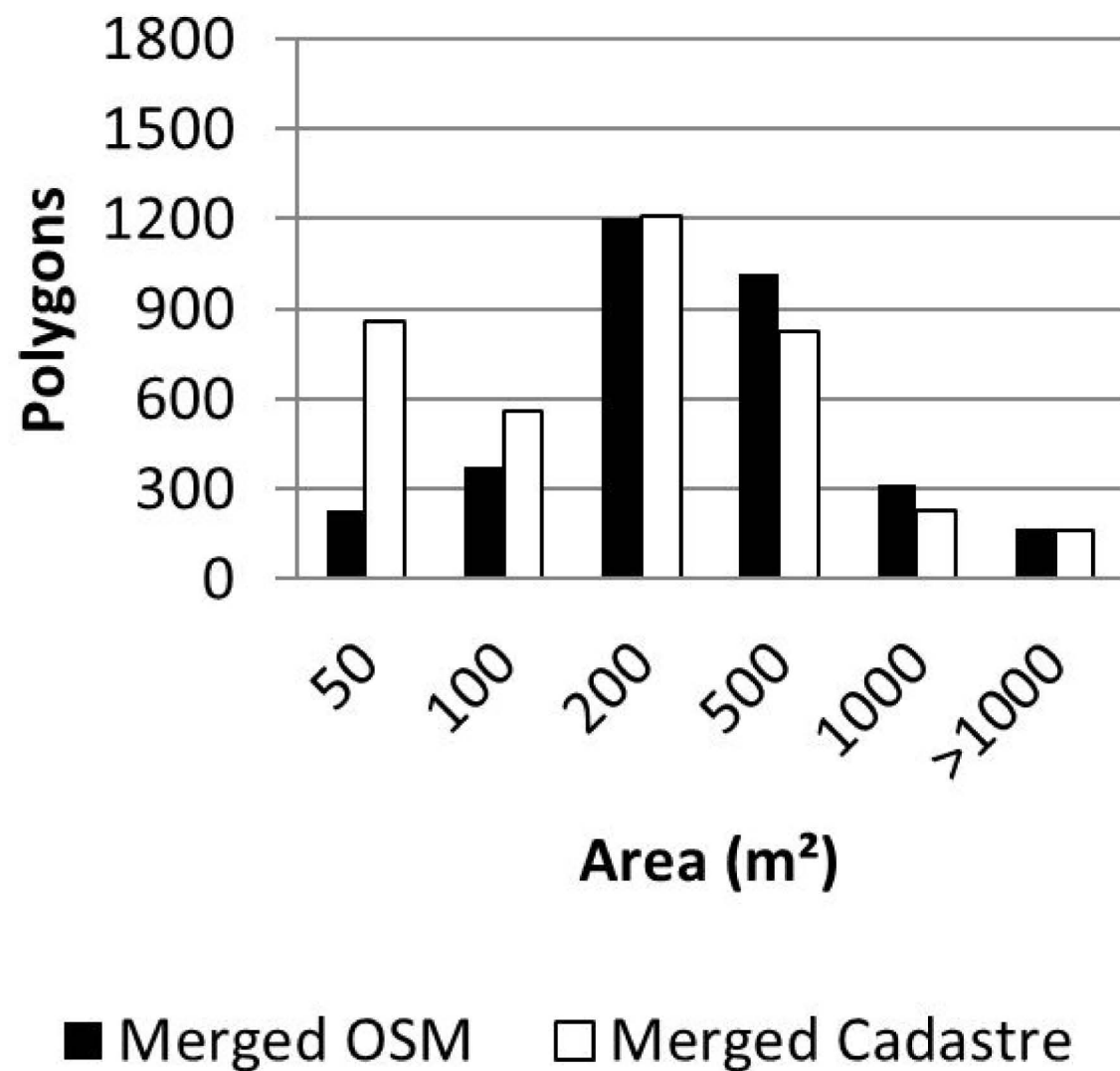
(c)



(a)

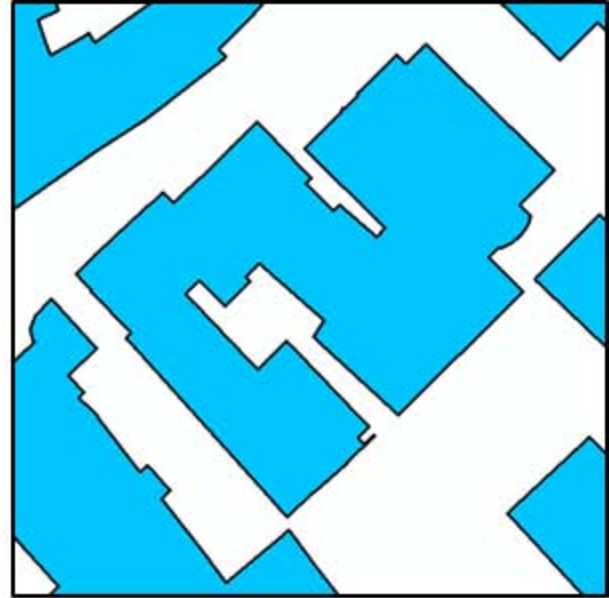
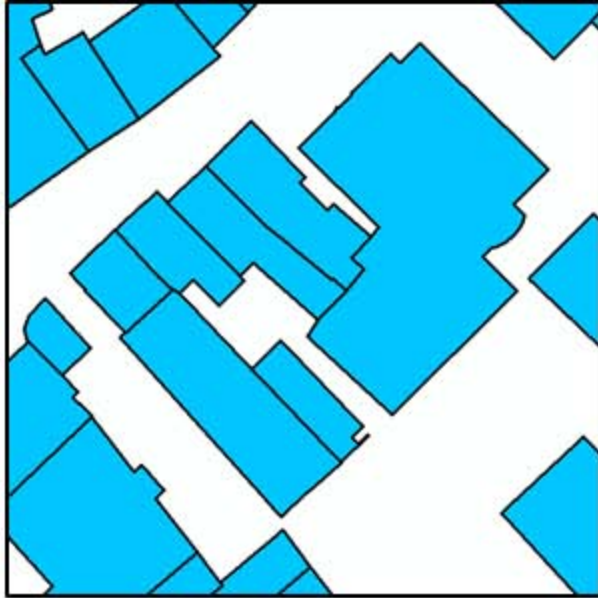


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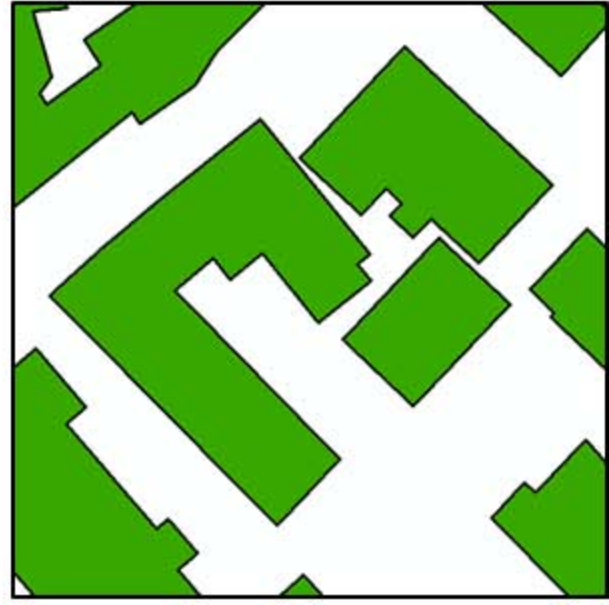
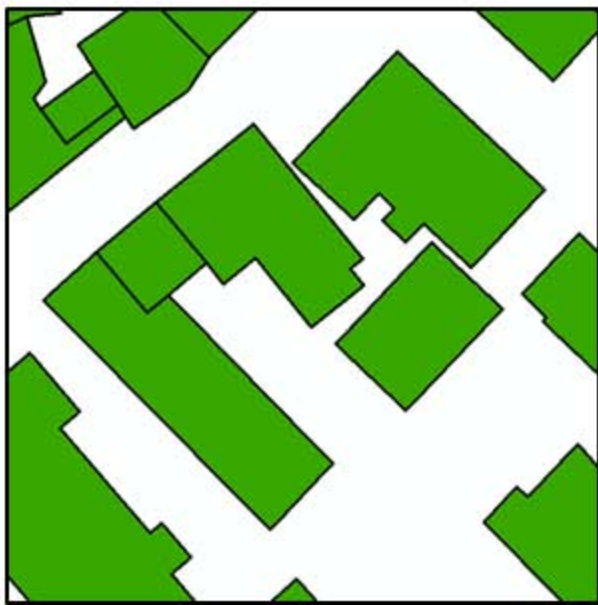




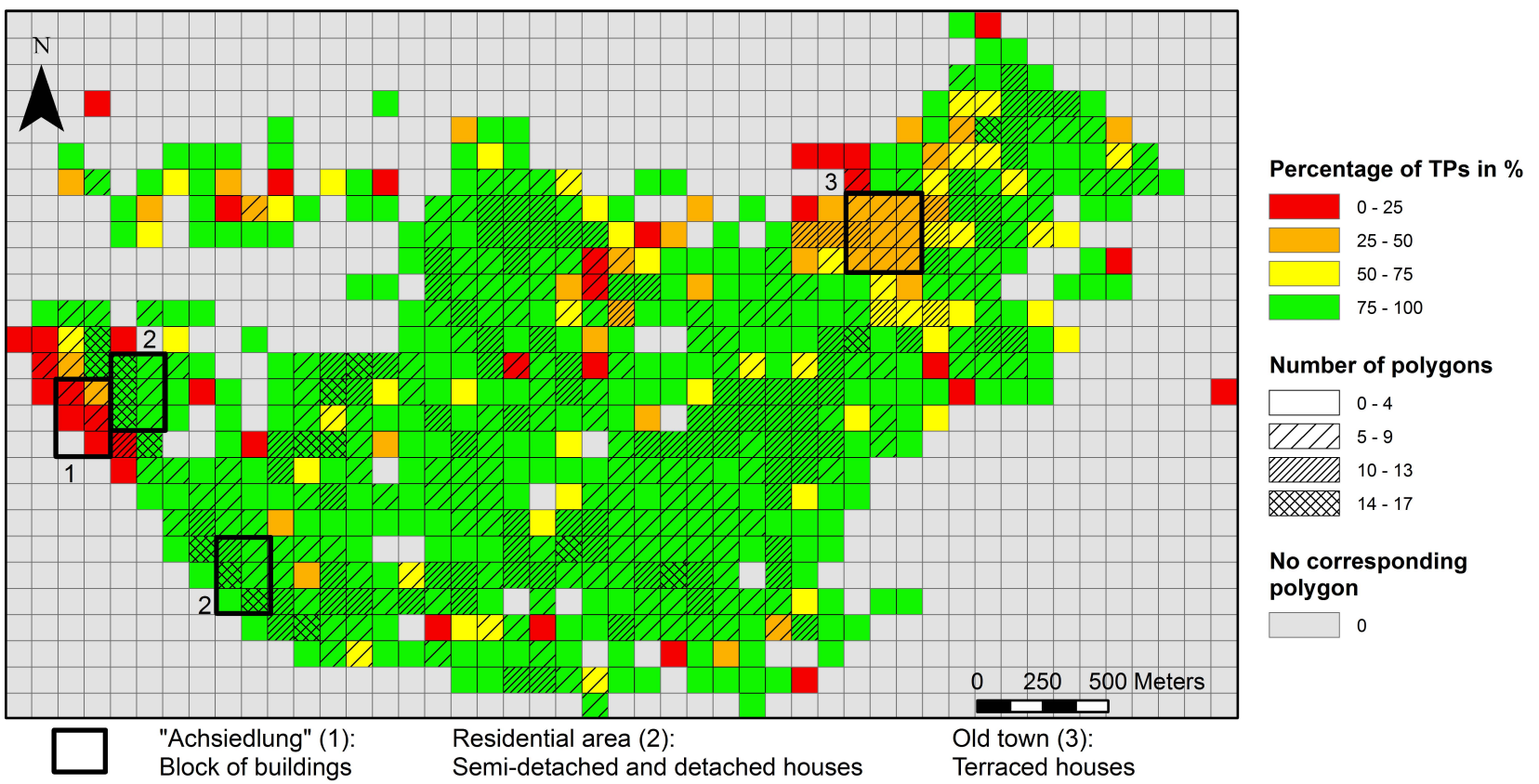
Cadastre

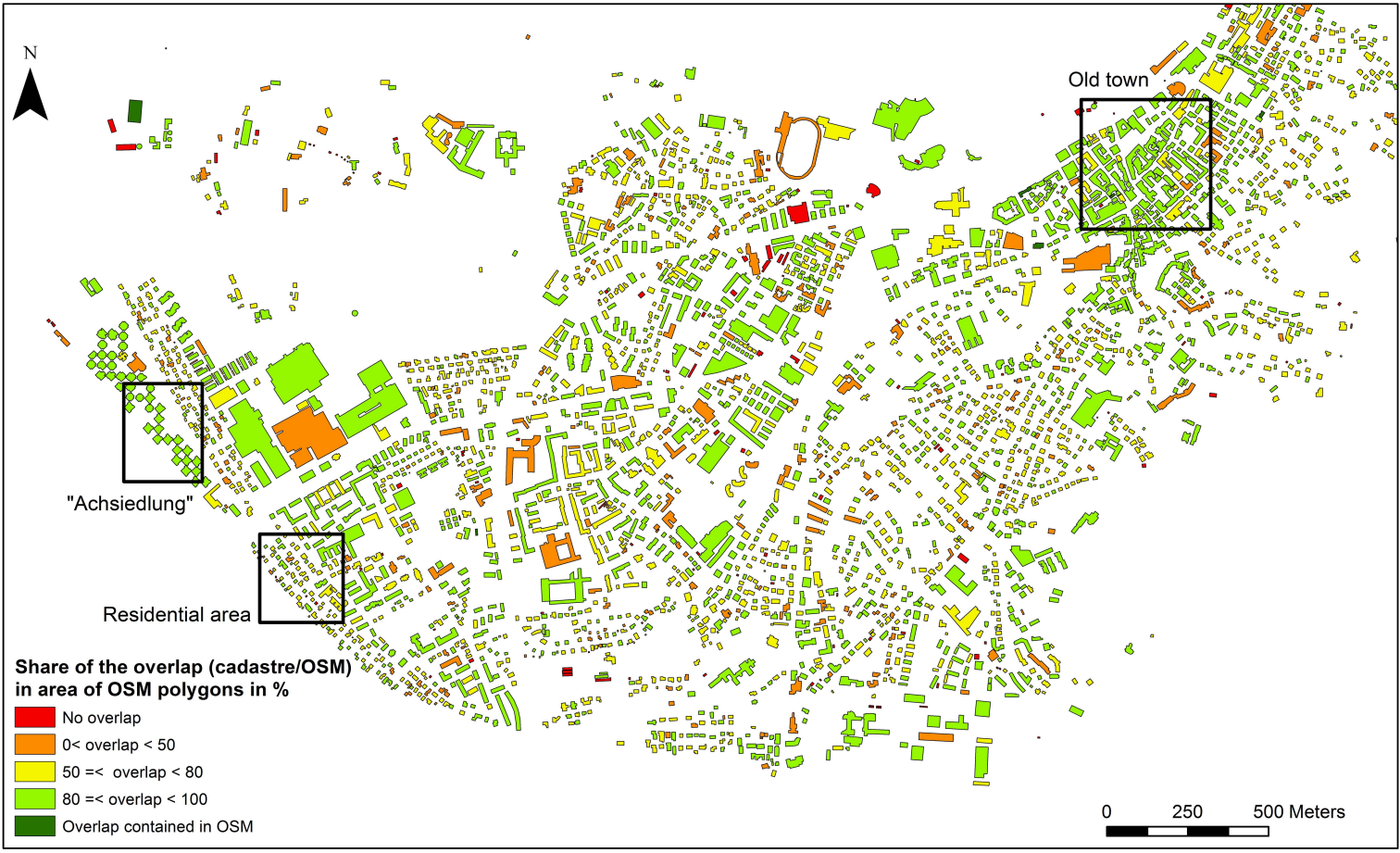


OSM



*Merging*



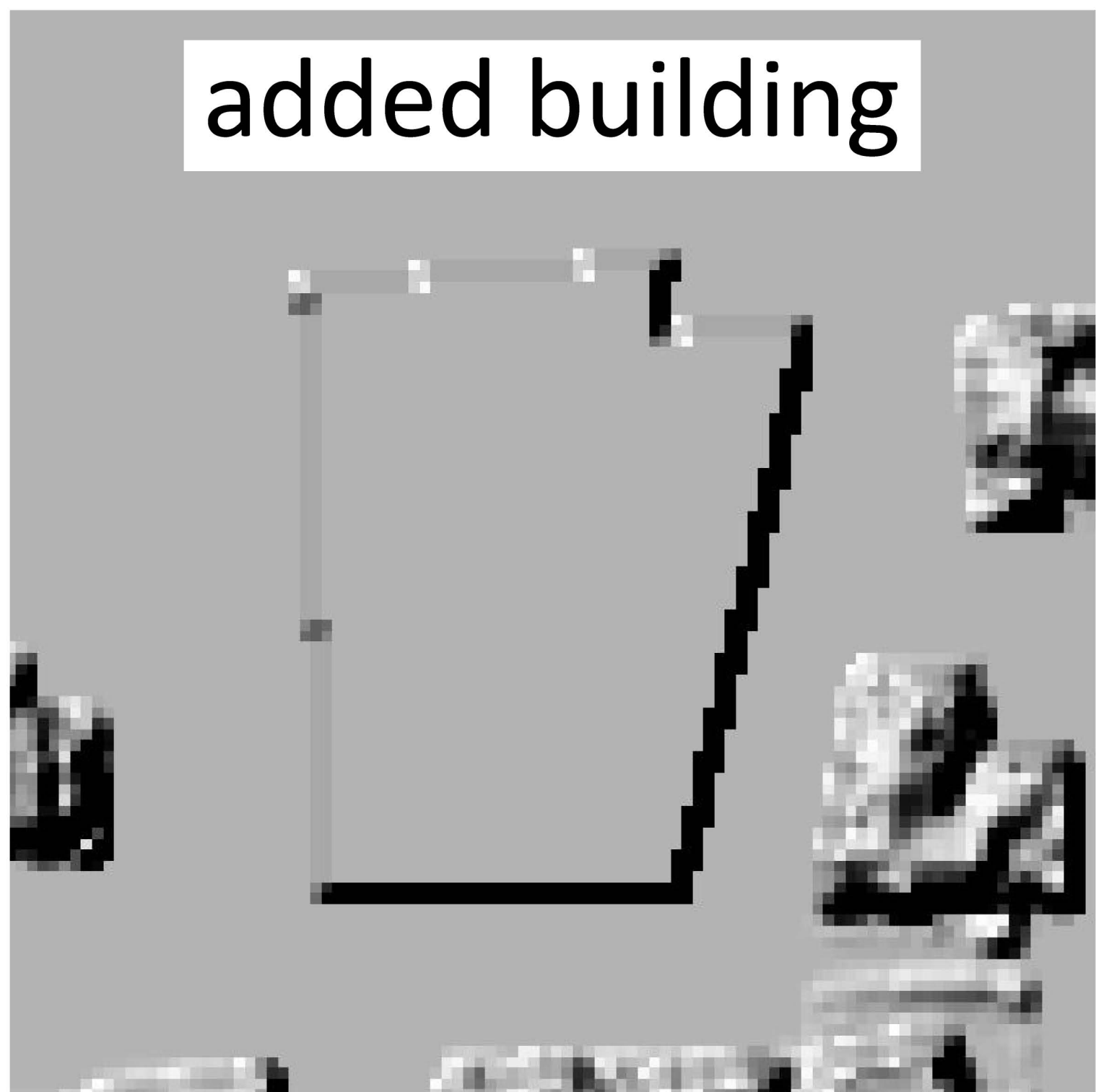




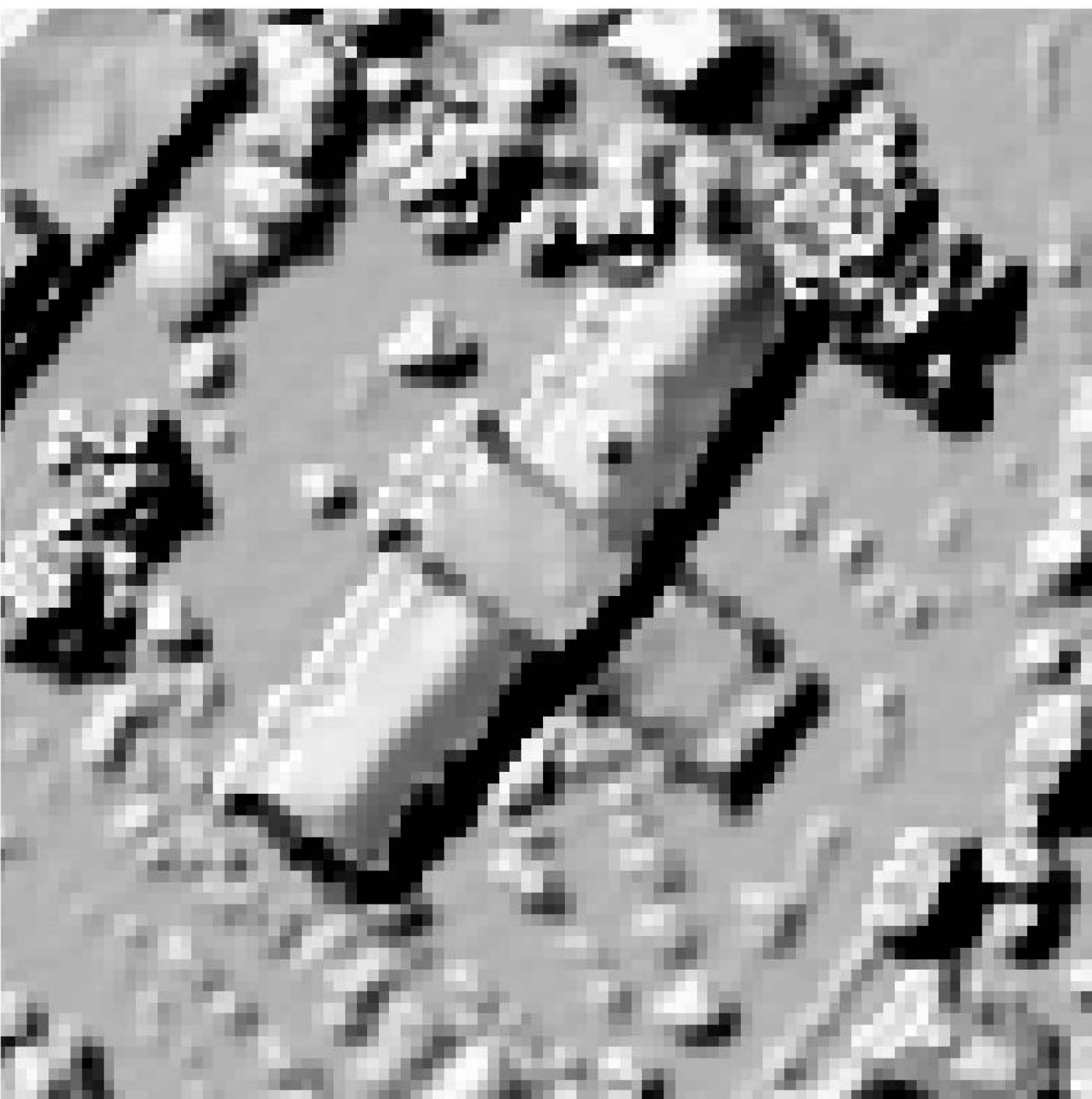
(a)



(b)



(c)



(d)

