Computers, Environment and Urban Systems 99 (2023) 101893

Contents lists available at ScienceDirect

Computers, Environment and Urban Systems

journal homepage: www.elsevier.com/locate/ceus

The Individual Walkable Neighborhood - Evaluating people-centered spatial units focusing on urban density

Ariane Droin *, Michael Wurm, Hannes Taubenböck

German Aerospace Center (DLR), German Remote Sensing Data Center (DFD), 82234 Oberpfaffenhofen, Germany

A R T I C L E I N F O

Keywords:
People-centered density
Individual walkable neighborhood
Urban structure
Navigation
Floor area ratio

A B S T R A C T

Urban planners are concerned to design the city in a way that supports quality of life. To catch how the settings of elements in space influence our subjective perception is difficult to evaluate, especially since objective measures are normally calculated at arbitrary scales. To better focus on the actual surrounding of individuals, people-centered reference areas are needed. The current study presents a comparison of three different people-centered reference areas which vary in their generalization of space: the Buffer, the Convex Hull of a routing network, and the "Individual Walkable Neighborhood". The latter reference areas are based on the streets an individual can reach within a certain amount of time. We compare the 3D-density of these three different reference areas and of arbitrary reference areas like city blocks in a quantitative and geographical way for the city of Munich. With this we can clearly show that it is crucial to focus on such people-centered reference areas, and that even at this very small scale big differences in density values can occur. Using navigational principles, a much more lifelike and realistic representation of the subjective neighborhood can be achieved, which should provide a basis for urban practitioners when combining objective variables to the subjective perception.

1. Introduction

The concept of density is widely used in urban research and planning as it *"relates the geography of spatial activities to the geometry of places through the built environment"* (Batty, 2009). It is a measure based on physical principles where a number of specific units is related to a reference area. The relatively easy implementation of the concept of density led to a variety of units of density measurements used by policymakers, practitioners, and academics to promote and argue for urbanization regulations and plans (e.g. Jacobs, 1961; Unwin, 1912). The variety of numerators that can be used for density calculations is huge and scholars like Churchman (1999) and Forsyth (2003) tried to disentangle the jungle of density definitions, calculations, and concepts by trying to give inclusive overviews. Nevertheless, no clear and consistent definition of density in urban planning and research exists up to date, despite some efforts to conceptualize consistent tools and methods which were especially supposed to enhance comparability by encompassing different aspects of density (e.g. Angel, Lamson-Hall, & Blanco, 2021; Boyko & Cooper, 2011; Dovey & Pafka, 2014; Taubenböck, Standfuß, Klotz, & Wurm, 2016).

Notwithstanding the multitude of possible numerators (e.g. built environment, population, jobs, etc.) that can be used for density calculation, another aspect of density often overlooked by practitioners and politicians and criticized and discussed by scholars is the denominator (e.g. Churchman, 1999; Forsyth, 2003). The denominator for density is defined as the reference area, which makes density per se an aggregate measure. The reference area can be chosen arbitrarily (administrative units, grid cells, catchment areas, etc.). Aggregate measures are affected by a generic problem which in geographical terms is often related to as the "modifiable areal unit problem" (MAUP) which can cause serious inconsistencies and misinformation. It has first been described by Gehlke and Biehl (1934) and thoroughly researched by Openshaw (1984) among others like Zhang and Kukadia (2005). In general, there are two main effects in regard to MAUP: the scaling and the zoning effect. The first relates to the modification of the pattern underlying the change in scale (aggregation or disaggregation), which in turn influences the resulting values. An aspect that is also shown in the seminal work of Craig (1984) for averaging population densities. The latter describes that even at the same scale, the different possibilities of setting boundaries (e.g. administrative boundaries, postal codes or grid cells) can have a significant impact on the result. In most cases, the frequent occurrence of MAUP can be traced back to the lack or scarcity of fine-

* Corresponding author.
E-mail addresses: ariane.droin@dlr.de (A. Droin), michael.wurm@dlr.de (M. Wurm), hannes.taubenboeck@dlr.de (H. Taubenböck).

https://doi.org/10.1016/j.compenvurbsys.2022.101893
Received 24 May 2022; Received in revised form 25 August 2022; Accepted 28 September 2022
Available online 21 October 2022

scale data (often data is only available at an administrative or coarse grid level). Taubenböck et al. (2019) researched how actual morphological urban areas vary from their respective administrative representation. The results indicated that density measurements, for example, can be greatly obscured and are not comparable when using administrative areas as a reference (see also Forstall, Greene, & Pick, 2009). Further, Krehl, Siedentop, Taubenböck, and Wurm (2016), Pafka (2020) and Wurm, d'Angelo, Reinartz, and Taubenböck (2014) clearly show with their research that the small-scale variability of built densities can be biased when studies are based on administrative units, whereas urban concentrations can be more accurately depicted using smaller-scaled grid cells, for example.

Policies concerning densities in urban planning are determined by considerations of sustainability (e.g. Haughton & Hunter, 2003; Howley, Scott, & Redmond, 2009; Williams, Burton, & Jenks, 2000) and thus, by the carrying capacity of the urban system (Oh, Jeong, Lee, Lee, & Choi, 2005; Wei, Huang, Lam, & Yuan, 2015) on the one hand (especially since higher densities are advocated for in the Sustainable Development Goals), and by the satisfaction of the population on the other (e.g. Bramley, Dempsey, Power, Brown, & Watkins, 2009; El Din, Shalaby, Farouh, & Elariane, 2013), as neighborhoods, cities or locations in general are always in competition with one another. However, policies often do not differentiate between the system (the physical) and the life world (the user-related) (Habermas, 1985) and therefore, they do not consider the perceptions and feelings of individuals in regard to their surrounding (Boyko & Cooper, 2011). As Weeks (2010) stated, "*Humans transform the environment; and are then transformed by the environment.*" The assumption is that there is a clear influence by our physical surrounding neighborhood (whether social or architectural) on our subjective perception. This has been referred to as the "*perceived density*" by Rapoport (1975), as the environment is judged against the personal norms of each individual. Stamps conducted several studies using different kinds of stimuli (photographs or simulated scenes) to assess, for example, the preferences of the design of streetscapes (e.g. Stamps, 1997) or the effects of spaciousness vs. enclosure on the perception (e.g. Stamps, 2001; Stamps, 2005; Stamps, 2010), among others. Further, studies tried to relate the measured and thus objective built-up density, often also related to as compactness, on the subjective perception (e.g. Lee et al., 2017; McCrea, Shyy, & Stimson, 2006; Mouratidis, 2018a, 2018b, 2019; Wurm et al., 2021). McCrea et al. (2006) found weak relationships between the objective reality and the resident's perception. They state that the findings, however, should be considered carefully, as they do not include individual characteristics of the inhabitants. Mouratidis (2019) did not find significant relationships between compactness and subjective well-being either. This problem can be related to the aforementioned MAUP, as the chosen reference areas are too broad in scale to represent the actual density as perceived by the interviewees. In their analysis of 67 monocentric cities in Germany, however, Wurm et al. (2021) showed that when density values reach approximately 70% of the Floor Area Ratio (FAR) of the city center, residents feel that they live "outside of the city center", regardless of the size of the city. Therefore, we can conclude that the perception of individuals is indeed valuable, as they can relate their surroundings to the rest of the city. To tackle the problem of scale in regard to perceived density, Pafka (2020) proposes the "Urban Experiential Density" (UED) measure, using fixed grids of 100 × 100 m, and thus also enhancing inter-city comparability. He concludes by arguing for a re-examination by the urban planners of the imposed ordinances on densities in order to include the actual experienced or perceived density. Plane and Mu (2021) outline in their work that nowadays we live a very scale-dependent life, especially since the virtual world has an increasing impact on our daily lives. They promote to use people-based density starting from a given location-point and to assess the reachable areas by different modes of transportation using time-distance thresholds. Using the Tucson metropolitan area, they show the differences in people-based density using different distance thresholds based on the Euclidean distance which reflect the different scales at which we live. Clear differences in the generated patterns can be detected and they call for a further investigation of this perspective.

We follow these calls of Pafka (2020) and Plane and Mu (2021), as it can be assumed that the weak relationships between objective urban characteristics and subjective urban attributes are likely related to the use of inadequate reference areas which are not people-centered. Thus, in this paper we investigate the differences of built-up density using three different people-centered reference areas which vary in their generalization of space. Instead of being determined by official boundaries like administrative areas or arbitrary areas like grid cells, they focus on the individual neighborhood of each citizen. Further, we also compare the densities of people-centered reference areas to the density of city blocks as arbitrary reference areas.

2. The conceptualization of people-centered reference areas

To illustrate the concept, let us take a grid cell of 500 × 500 m and place it on an area where the Berlin Wall once ran through. If we compare the built-up density before and after its fall, it will not have changed considerably, but the feeling of the place changed radically for people living there: the permeability of the area fundamentally altered (Ståhle, 2008; Stamps, 2005). It went from an impenetrable barrier to an open space and people could freely move from East to West Berlin. This very vivid example shows that even if the physical density does not change, the perceived density of a place can change substantially.

The concept of subjective perception has also been addressed by Lynch (1960) when he introduced the idea of "mental maps". He describes that when we navigate through a city, there are five main components that help us draw a mental map: paths (e.g. streets), nodes (e.g. junctions), edges (e.g. railway tracks, rivers, highways (see Fig. 1-A/B/D)), landmarks (e.g. a mountain, a monument) and districts (e.g. downtown (see Fig. 1-C)). That way, every individual has their own mental map of his/her neighborhood, in which density is perceived. Focusing on the three first components of Lynch's mental maps, we can see a connection to the concept of navigation: paths are the areas where we walk, nodes are certain points where we can change direction, making new paths available to us, and edges are barriers that prevent us from accessing certain areas. Administrative areas, grid cells (as used in the approach by Pafka (2020)), or other artificial boundaries do not take into consideration those barriers that make certain areas inaccessible. Rapoport (1975) acknowledges these barriers as well. He argues that there are three types of boundaries or barriers linked to perceived density: the choice of reference areas, physical boundaries like fences, and social boundaries (e.g. different social groups that do not interact with one another).

Building up on the work of Plane and Mu (2021), focusing on the individual, there are different possibilities to capture their immediate surrounding, with different implications of the consideration of these aforementioned barriers. The most simplistic representation is a buffer which corresponds to a fictional representation of the space around the individual, assuming that there are no barriers and that the individual can walk around freely. A more nuanced representations of the surrounding area of an individual can be achieved by applying a routing algorithm to create an individual neighborhood. This area can actually be reached on foot by a person, considering these barriers in combination with the spatial layout of the streets. Routing, also often referred to as guidance, is one of the fundamental components of navigation (Hofmann-Wellenhoff, Legat, & Wieser, 2003). Hofmann-Wellenhoff et al. (2003) state that for successful routing, a graph is needed to generate routable networks. They consist of a set of edges (not to be confused with the edges from Lynch (1960)) and nodes, where the first represent streets and paths in the real world and the latter represent intersections of edges. The most common routing applications are shortest-path problems, where the most direct way between two nodes is returned (Hofmann-Wellenhoff et al., 2003), but there is a great

Fig. 1. Different urban morphologies shape our subjective perception. Further, barriers lower the permeability of space. (A) Modern high-rise multifamily buildings with a railway-barrier. (B) Multi-family homes with a small river as barrier. (C) Perimeter block development, with inner courtyards that are blocked by high facades. (D) Multi-family homes with a highway as barrier.

variation of navigational tasks, one of which is the generation of an isochrone network. An isochrone network represents all points in space that can be reached within a certain amount of time (e.g. 5 min) from a given starting point (Gamper, Böhlen, Cometti, & Innerebner, 2011). Using these calculated isochrones two different people-centered references areas can be generated: One representation is the so called Convex Hull (connecting the outermost points of the network) as proposed by Berghauser Pont and Marcus (2014). This approach may still consider big barriers like highways or railways, but small-scale barriers (like enclosed areas) are disregarded.

In order to relate objective urban characteristics to subjective perception of space as close to reality as possible, we propose to use the generated network itself which we, for simplistic reason will refer to as the so called "Individual Walkable Neighborhood" (IWN). In general, this concept refers to the actual space surrounding a residence or place of work that is truly within walking distance. As such, it excludes all elements of the environment which lie within a certain radius but are not accessible on foot, like enclosed courtyards or areas blocked by traffic infrastructure or natural elements (e.g. rivers) which cannot be crossed.

3. Experimental setup and data

We decided to apply our concept to the city of Munich, Germany, by setting a starting point every 50 m within the administrative boundary of the city. To reduce the number of starting points, we use only points that are within city blocks which the Urban Atlas (UA) defines as "*urban fabric*". The UA is a high-resolution land use product of the Copernicus Land Monitoring Service (CLMS) of the European Union covering the functional urban areas (FUA) of approximately 800 cities with a minimum mapping unit of 0.25 ha. The "*urban fabric*" class includes city centers, downtown areas, residential areas and areas with partial residential use and is divided into 5 subclasses which are differentiated by their degree of soil sealing (European Union, 2020). For each of the points, we then generate a Buffer and 5 min isochrones (Convex Hull and IWN) with an average walking speed of 4.5 km/h (average walking speed for adults as investigated by Schimpl et al., 2011) using the osmnx package in python (Boeing, 2018) (see Fig. 3). Based on the walking speed of 4.5 km/h the buffer radius is 375 m. For the edges of the navigational networks, we only consider walkable paths that are publicly accessible, excluding non-pedestrian streets like highways and private paths (for other modes of transportation the average speed as well as the used edges can be adapted). Finally, we calculate the 3D density (floor area ratio (FAR)) as a metric to investigate the different aspects of the three people-centered reference areas.

As a data source for FAR, we use the official cadastral building model (level of detail 1 (LoD1)), which includes information about the building ground floor area as well as the mean height of the building (BKG, 2021). To calculate the floor areas, we use OpenStreetMap (OSM) buildings where the number of floors is denoted and where the area does not vary >10% from the area of the respective LoD1 building. We relate the number of floors from these buildings to the building height of the LoD1 and generate a regression equation (Wurm et al., 2021; Wurm, Taubenböck, Schardt, Esch, & Dech, 2011). We can then extrapolate the information about the number of floors to all buildings. Finally, floor area (FA) is calculated by multiplying the building ground area with the respective number of floors. If the boundaries of the reference areas intersect with buildings, we calculate the proportional floor area (FA) of the building within the reference area. With these comparisons, we aim to expose the importance of calculating people-centered densities at the individual level and show that even at that small scale, variations are still occurring depending on the chosen reference areas.

For each starting point, the IWNs contain only the streets that can be reached on foot within 5 min. To generate polygons and to have a realistic representation of the field of view of an individual walking around a neighborhood, a buffer is used around the streets. We increase the buffer distance in 5-m increments from 5 to 50 m, calculating the FAR at each step, to empirically determine the impact of the buffer width (see Fig. 2). We will use a buffer width of 25 m, as we argue that it is a good representation of the field of view, leaving out enclosed areas like courtyards (see Fig. 4 for an example).

Further, to research the impact of different urban densities on the

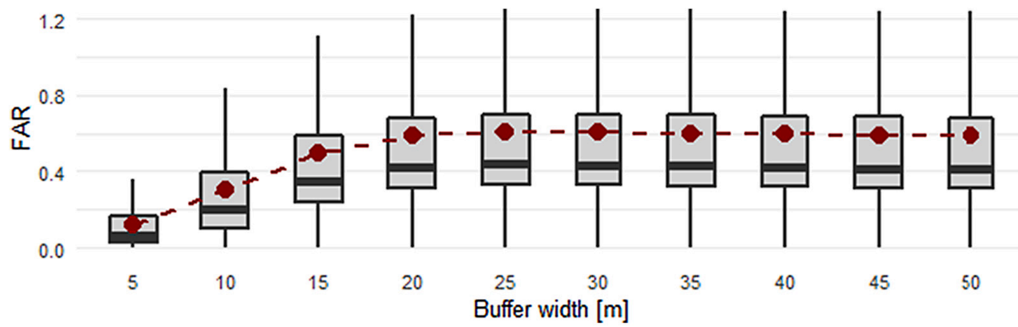

Fig. 2. FAR for different buffer widths around the streets for 5 min walking time. Red dots represent the mean. For buffer widths under 20 m, the FAR increases considerably, whereas it stays relatively constant above that limit. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

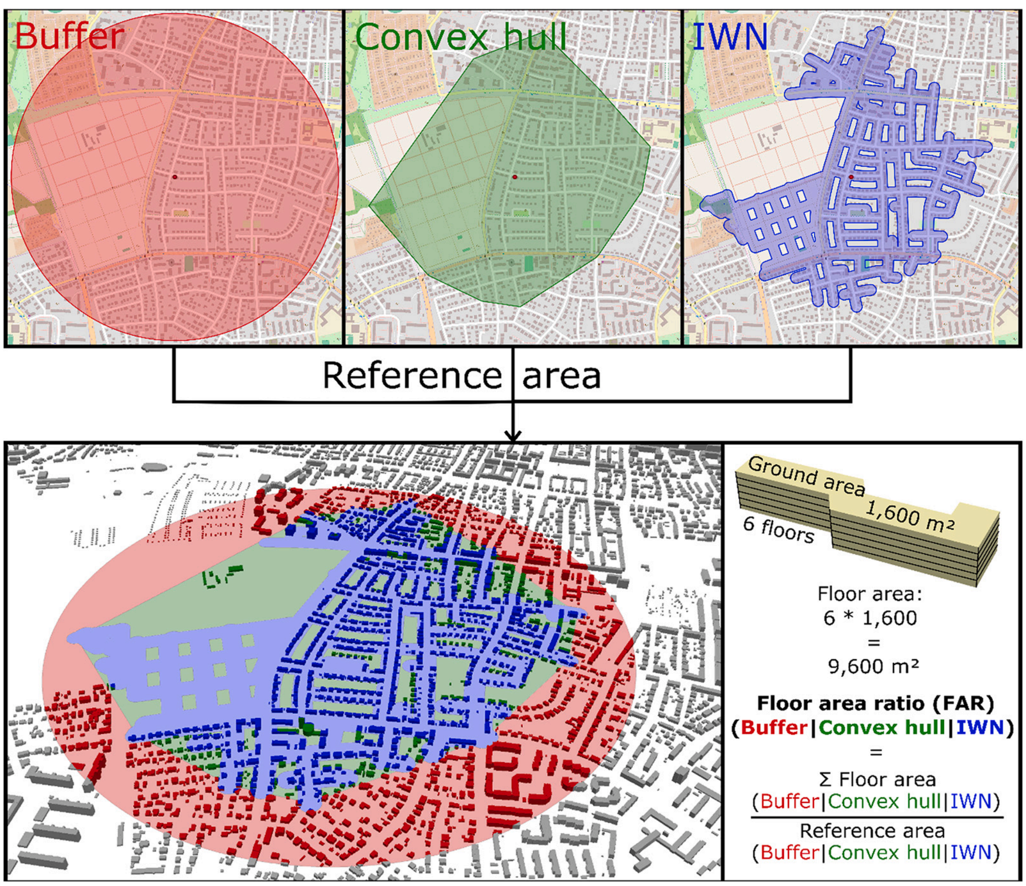

Fig. 3. Different reference areas and FAR calculation. The Buffer corresponding to a "barrier-free" space, the Convex Hull representing the enclosed area of the network, however, including areas that may not be perceived by an individual, and the IWN, considering those small-scale barriers. The algorithm differentiates between publicly accessible paths and private paths. This can be seen in the top row, where only the lower part of the grid in the western part can be accessed as the upper part is not publicly available (the paths are also colored differently). The lower image shows a perspective view of the 3D LoD building model and the spatial reference areas (left) and the FAR calculation (right). The calculation is conducted for the three individual reference areas using the sum of the FA of the buildings intersecting the respective reference area. Basemap: ©OSM. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

different reference areas, we differentiate the "*urban fabric*" subclasses from the UA as follows: (a) *very low density* ("Discontinuous very low density urban fabric (S.L. : $<$ 10%)" and "Discontinuous low density urban fabric (S.L. : 10% - 30%)"), (b) *low density* ("Discontinuous medium density urban fabric (S.L. : 30% - 50%)"), (c) *high density* ("Discontinuous dense urban fabric (S.L. : 50% - 80%)") and (d) *very high density* ("Continuous urban fabric (S.L. : $>$ 80%)"). For the different reference areas and the different urban densities, we investigate the FAR values as well as the differences between the FARs for each starting point.

Finally, we argue that an important aspect of these individual reference areas is that they consider the immediate neighborhood of the individuals, whereas administrative or other artificially defined areas arbitrarily cut off densities especially near their boundaries. An individual living near a boundary is still impacted by the physical space and built characteristics on the other side of the boundary, which is disregarded when using such reference areas. We show this by comparing the mean FAR densities for the different urban density classes of the respective UA city blocks and the mean densities of the individual reference areas (using the means of the different starting points within each UA block).

4. Results

We analyse the implications of the different reference areas in a quantitative way and in their geographical context. We then also compare the results to density values as defined by the blocks from the UA.

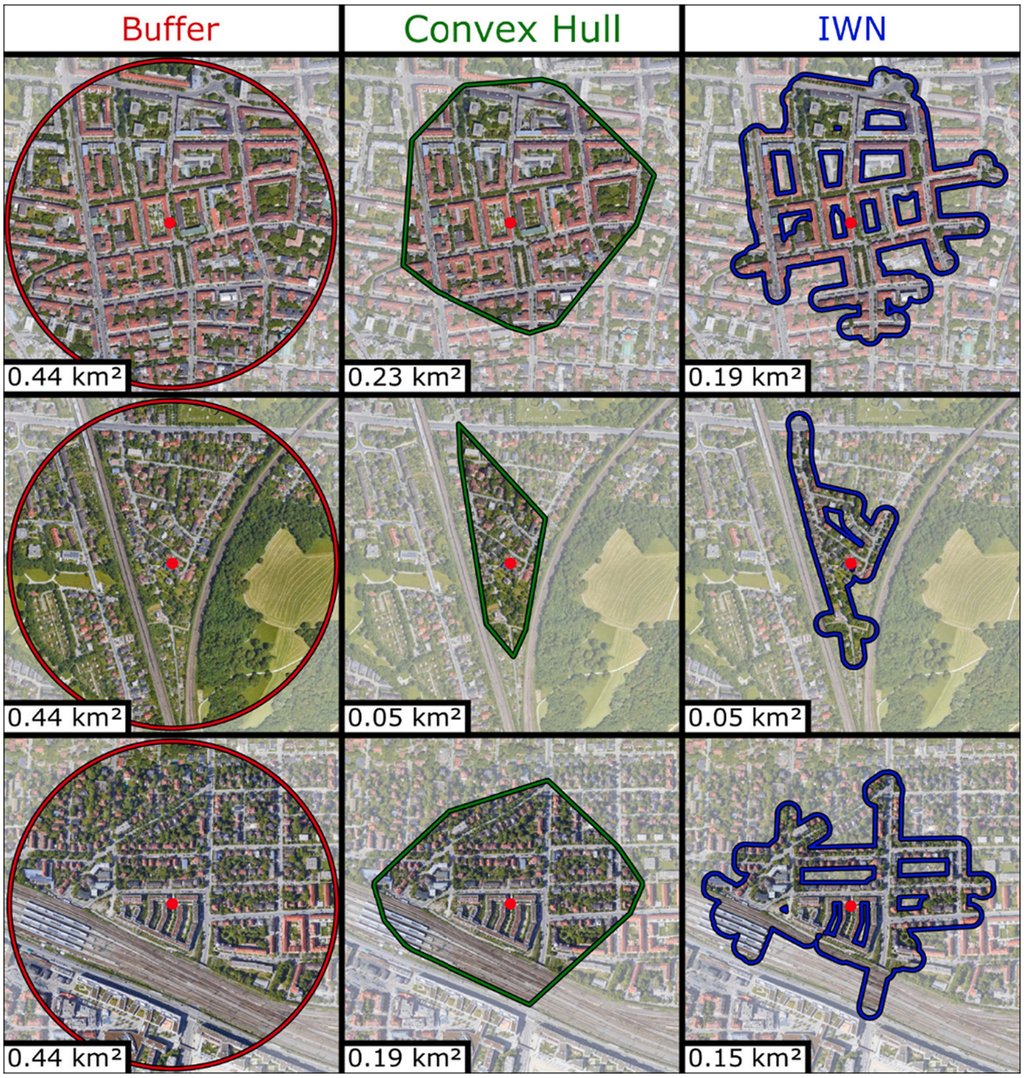

Fig. 4. Examples showing the different properties of the reference areas for 5 min walking distance. Non-reachable areas like courtyards or railways (apart from underground crossings) are not considered for the IWN reference area. Buffer reference areas assume that there are no barriers, causing big differences in the area considered. Basemap: Map data ©2015 Google. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.1. Shape and size of the three spatial concepts

Three different examples of the people-centered individual reference areas are depicted in Fig. 4. The top row depicts a block development. What is immediately apparent is that the IWN does not include the inaccessible courtyards, whereas the Convex Hull encloses the entire area. Because of the layout of the streets, the reference areas based on a network (IWN and Convex Hull) do not extend to the south as far as in the Buffer model. The middle row shows a residential area that is surrounded by barriers (two railways to the east and west respectively and a big street to the north). While the Buffer does not consider these barriers at all, the network-based reference areas show clearly that individuals living in this area are very restricted in their movement radius. The bottom row shows a combination of the two top rows with a clear barrier in the south which is more weighted in the Convex Hull approach than in the IWN. Additionally, the IWN excludes some private gardens in the northern part.

4.2. FAR densities

The calculated FAR values vary depending on the urban densities and the different reference areas (see Fig. 5). The FAR values for the Buffer reference areas clearly show a different pattern when compared to the network-based reference areas in lower density urban areas. Convex Hull and IWN densities tend to be very similar in these areas. With increasing urban density however, the FAR of the IWN reference areas clearly set themselves off from the Buffer and Convex-Hull FAR.

When we investigate the differences of the densities (FAR) between each Buffer and its corresponding network-based reference areas (Convex Hull and IWN), clear dependencies from the urban density can be recognized. The higher the urban density, the bigger the gaps become (see Fig. 6). Further, the distribution of FAR differences is generally more heterogeneous in higher urban densities.

4.3. Geographical differences

A cartographic representation of the geographical differences between the IWN and the Buffer FAR densities for the area of Munich is illustrated in Fig. 7. White areas represent areas where the FAR of the IWN and the Buffer are very similar. Orange areas represent areas where the FAR of the IWN is higher than the FAR of the Buffer, and in red areas, the FAR is higher in Buffer models than for the IWN. There are clear spatial patterns to be recognized. The FAR is measured higher for IWN along the aforementioned barriers: railways, highways, and rivers - areas with low permeability where diffusion into space is not simple or possible. A higher FAR for Buffer occurs mainly near industrial areas, which are not accessible to citizens and thus are not considered with the IWN model. As shown in Fig. 6 as well, we observe the biggest differences in the urban center, whereas peripheral areas are more homogenous, with more areas where no differences between the two reference

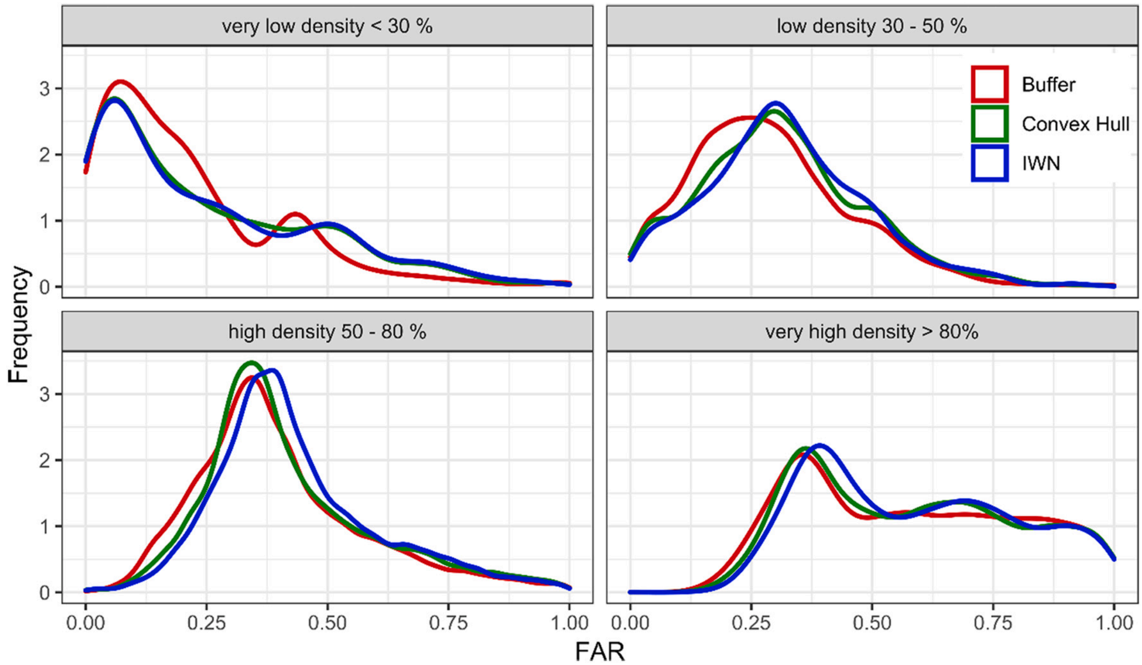

Fig. 5. Histograms of FAR for different urban densities based on the reference areas for 5 min walking distance. FAR are very similar in areas of low urban density for the network-based reference areas (top rows) with increasing FAR densities for IWN in high urban densities (bottom row). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

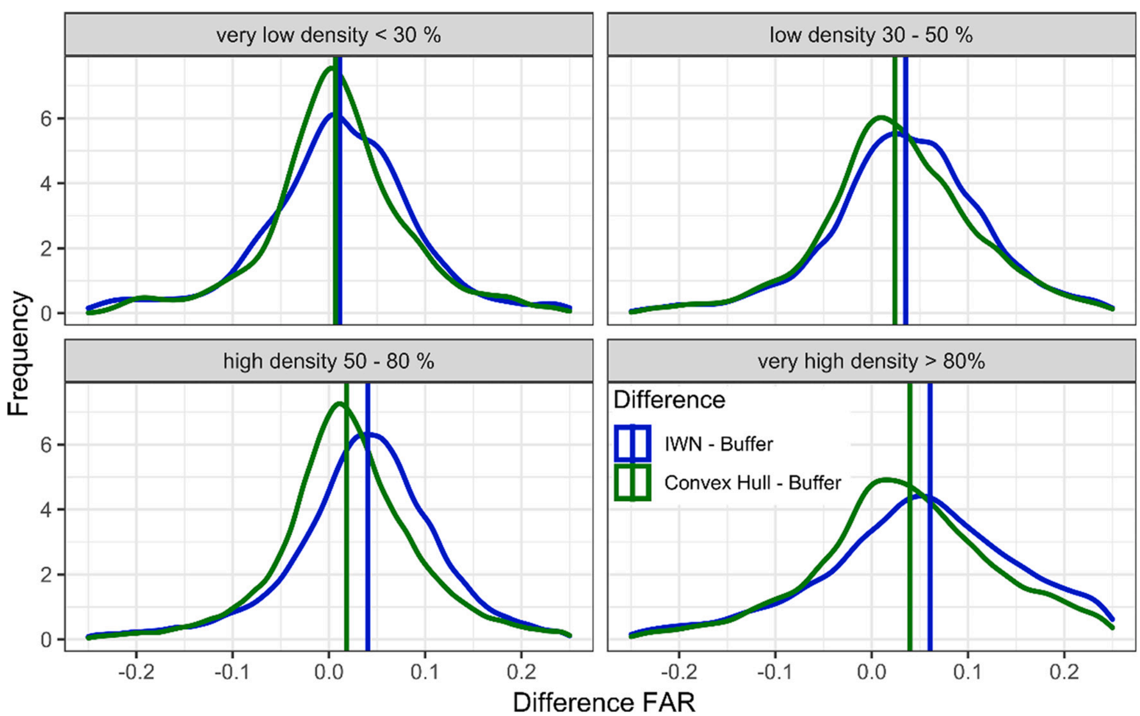

Fig. 6. Differences in FAR between Buffer and Convex Hull and IWN respectively. Vertical lines represent the median of the differences. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

areas occur.

The geographical distribution of FAR densities for the IWN approach shows high densities in the city center with a decrease towards the periphery and some local centers (see Fig. 8). Area A and B in Fig. 8 show that there are variations in the patterns of FAR between the different people-centered reference areas, as well as the density of the UA city blocks, on a small scale.

4.4. Mean densities of individual reference areas compared to mean UA block densities

In a last step, we calculated the differences between the mean FAR values of the three reference areas and the FAR of the respective UA city blocks (see Fig. 9) for the whole city. The top row shows the differences in mean FAR for the whole area of Munich for the different reference

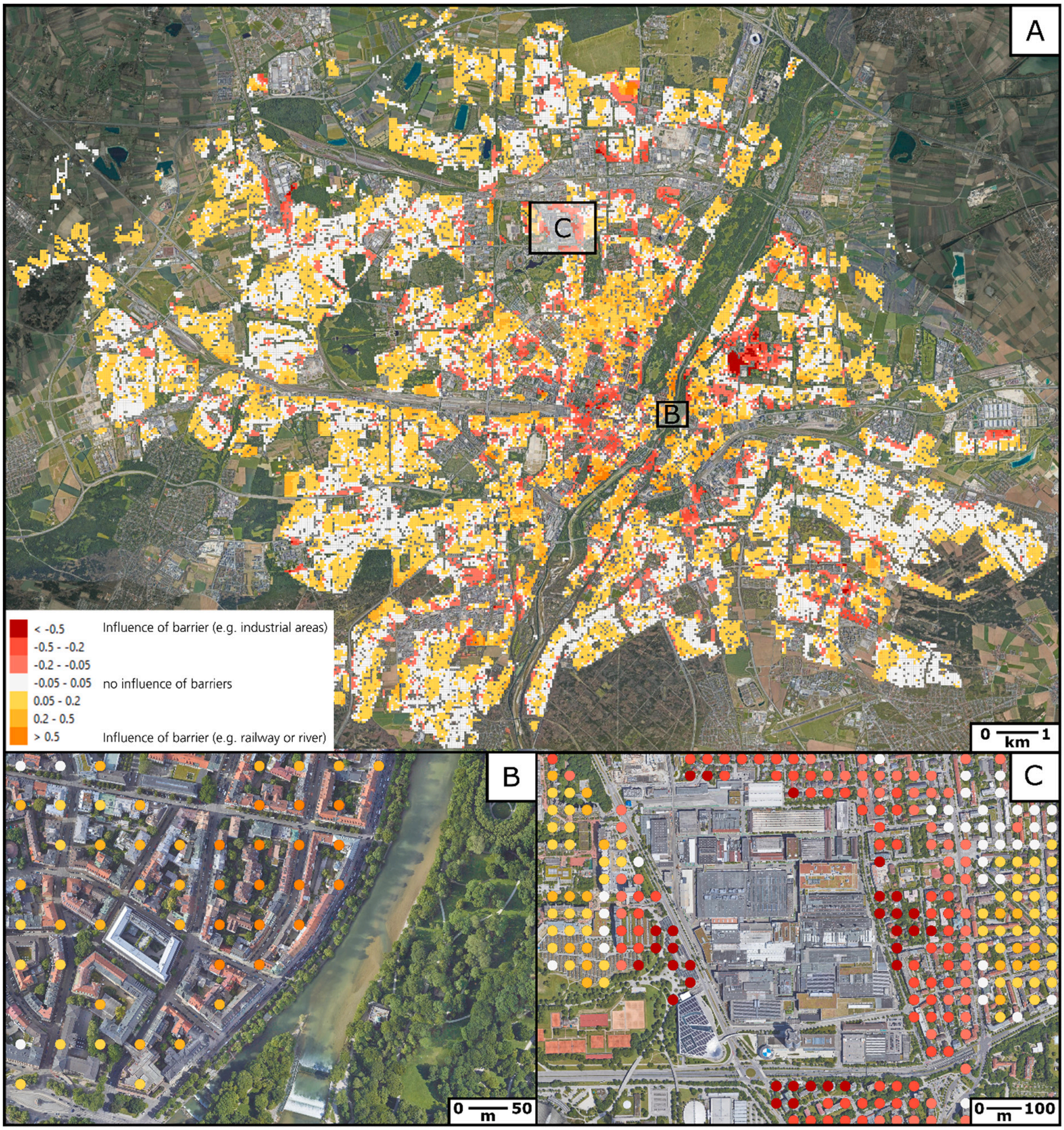

Fig. 7. (A) Cartographic representation of the geographical differences between FAR of IWN and FAR of the corresponding Buffer for each starting point in Munich. The green belt running from south to north represents the river Isar, which divides the city between east and west (see also (B)). Further, the city is divided by railway tracks running from east to west in the western part of the city. In these areas clear differnces between the Buffer FAR and the IWN FAR can be recognized, as the Buffer reaches into areas with no buildings. Industrial areas are often enclosed and lower the permeability (see (C)). FAR values differ in these areas as well between Buffer and IWN, as the Buffer reaches into areas with buildings. Map data ©2015 Google. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

areas. Mean FAR values are much higher for each of the UA blocks than for the individual reference areas. Differences between the three reference areas are comparatively small, with the lowest mean FAR values for the Convex Hull.

If we look at the mean FAR values per model for each level of urban density, we see that the corresponding UA block scores much higher than the other reference areas except for the *low densities,* where all models get roughly the same result. The highest discrepancy in mean density between the individual models can be found in the urban core with *very high densities*. This is also where the UA block mean density differs the most from the other three reference areas.

5. Discussion

In an ever-changing world with growing competition between cities, urban planners are asked to implement policies that keep places vital and their inhabitants happy. As stated by Forsyth (2003), perceived density is determined by physical aspects of the environment, landscaping, building type and design, as well as noise and aesthetics. To know how we perceive our surrounding neighborhood helps us to understand what emotional responses we will have and what aspects influence which feelings (e.g. Glass & Singer, 1972; Sherrod, 1974). Research trying to directly link objective parameters to the subjective perception did not result in satisfying results. Nevertheless, Wurm et al.

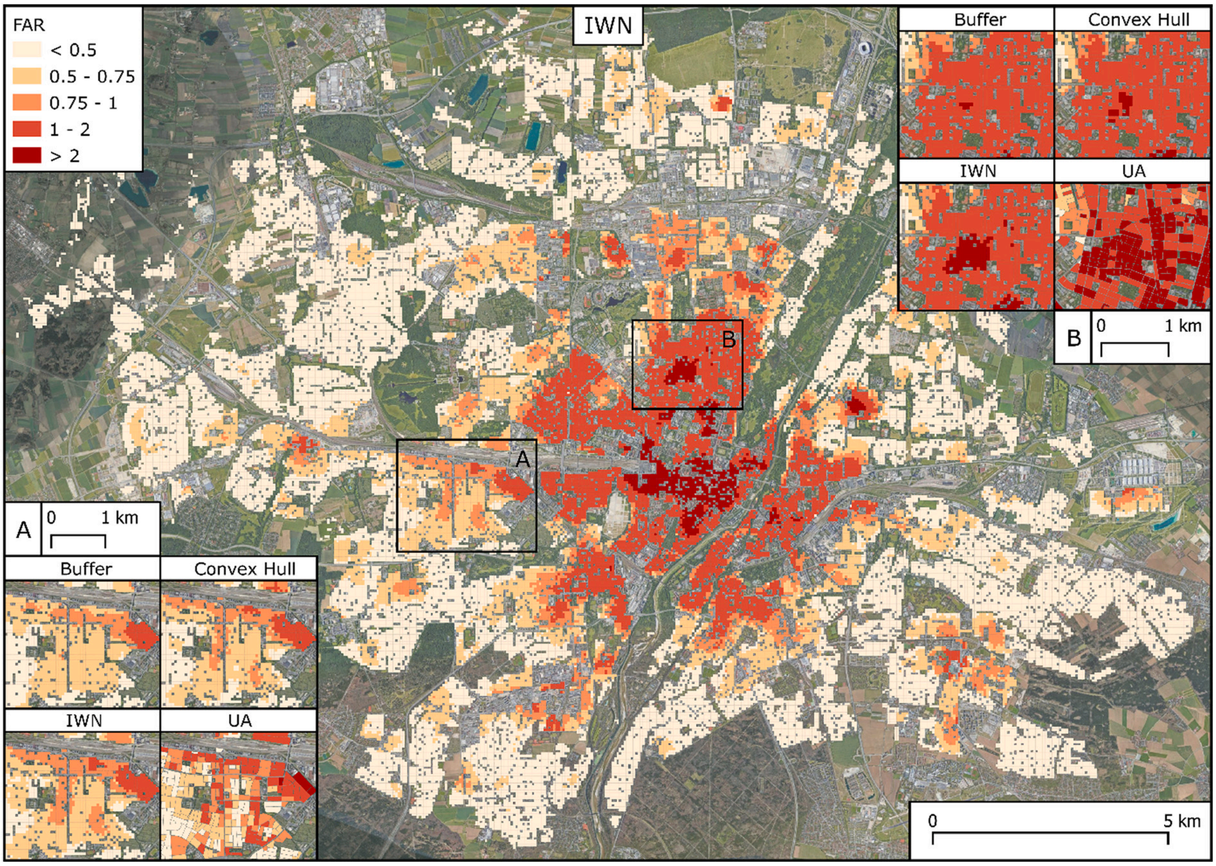

Fig. 8. FAR values for the IWN approach in Munich. Areas A and B show excerpts of the different FAR values for the different approaches. (A) Near the railway in the north the Buffer approach has lower densities compared to the navigational approaches (Convex Hull and IWN) as these do not reach as far into the railway area. The navigational approaches also show that bigger streets (in this case the straight line running from north to south) have an impact on the density calculation, due to the considerations of few crossings, as FAR values increase considerably in comparison to the Buffer. (B) shows the clear consideration of the influence of fenced off inner courtyards from the perimeter block development (as shown in Fig. 4 in the upper row). The UA city blocks have very high FAR densities as it combines relatively uniformly high buildings with small reference areas due to the street patterns in this urban structural type. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

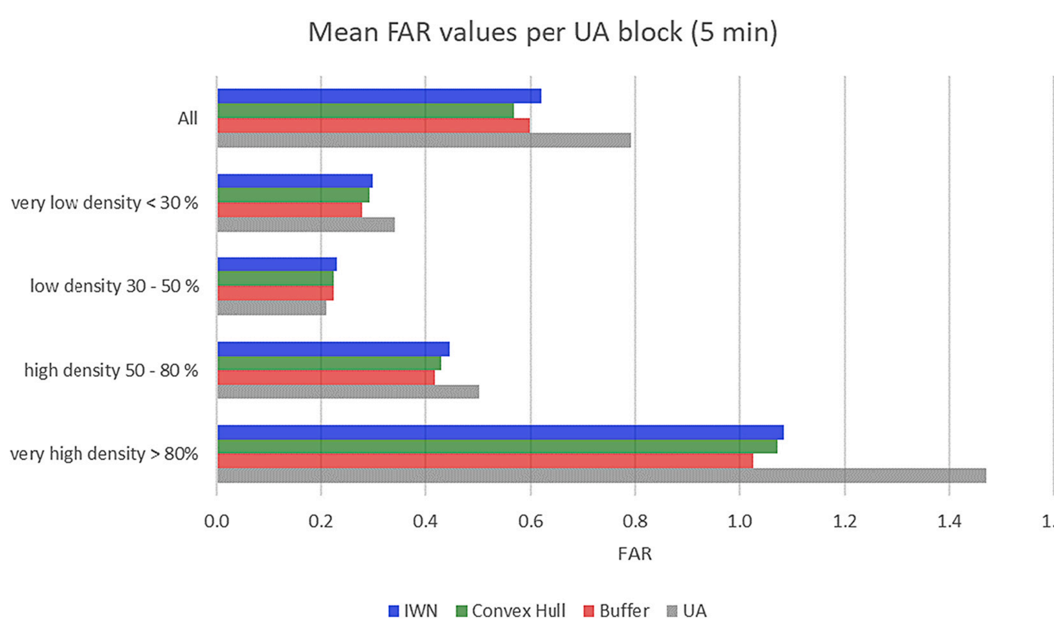

Fig. 9. Comparison of mean FAR values between different reference areas and the FAR within UA blocks. The last 4 rows show a differentiation depending on the urban density class of the UA. Mean UA block FAR values are considerably higher than FAR values based on the individual reference areas. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(2021) clearly showed with their research that if we do not try to identify direct correlations but attempt to look into this aspect from a different angle instead, there clearly seems to be a connection between perceived and physical density. However, research in this direction mostly focused on the actual variable (building density, density of people, infrastructural density, etc.) that was compared to the perceived density, rather than on the individual perception of that variable. We argue that before different aspects of the physical layout can be researched regarding their influence on our subjective evaluation, we need to find the ideal reference area based on which these characteristics can be calculated. To achieve this goal, we evaluated the objective differences in density for three different people-centered reference areas that represent the immediate surrounding neighborhood of each individual in a different degree of detail. With the IWN only those parts of our surrounding neighborhood we can visually ingest are taken into consideration and barriers like railways that hinder the permeability of space are considered as limiting factors. This can clearly be seen in Fig. 7, where the biggest differences between the fictional Buffer without barriers and the IWN are located near railways, rivers and industrial areas. On a smaller scale, the middle row of Fig. 4 and Fig. 8 also illustrates this quite clearly. With the work at hand we could show, that even at a very small scale differences occur between the chosen people-centered reference areas. Which reference area is used depends on the case at hand. While the Buffer approach is a computationally easy task and does not ingest a lot of saving space, it is more appropriate for micro-climatic and environmental studies as these reference areas are spatially comprehensive. The Convex-Hull approach is, in comparison to the IWN approach, more scalable as memory is less of an issue here and could thus, be used for studies conducting international comparisons, nevertheless considering areas that may be inaccessible to individuals. We argue that the IWN approach is the closest representation to what people probably actually perceive. Whether these differences in density values by the different reference areas really coincide with the subjective perception of the individual is suggested to be researched in future research studies. Therefore, these objective variables need to be combined with actual geographically located subjective perception.

With the calculation of FAR densities for different starting points in the area of Munich, we were able to clearly show that the concept of IWNs is better at displaying the small-scale variability of the direct surrounding neighborhood of each individual than other models. This difference is more distinct in higher-density areas. This can be attributed to the fact that in Munich, high-density residential areas are mostly constituted of perimeter blocks with big inner courtyards. As can be seen in Fig. 4 in the top row and Fig. 8-B, the IWN reference areas do not take into consideration such inaccessible spaces. To our mind, this depicts the reality quite well, as when we walk around our neighborhood, we cannot perceive these areas as they are blocked by the facades of surrounding buildings. We are aware that not every city has this kind of structural layout in its urban center and that the numbers may vary depending on the structural type. Nonetheless, we argue that with this example, we have shown the necessity of people-centered reference areas, especially since we demonstrated that the level of urban density has an impact on the differences between the individual reference areas.

We have also shown that it is important not to use arbitrary boundaries like administrative areas, grid cells, parcels, or city blocks to calculate variables if the aim is to assess an individual's perception of their surrounding neighborhood. Comparing the FAR densities of the UA city blocks to the individual reference areas shows that there are big differences, especially in very high- and very low-density areas. Therefore, it is very important to encompass areas that are outside of imagined boundaries such as administrative areas, as they are not physical barriers and our perception and mobility extend beyond them. People-centered reference areas are even useful if we use administrative boundaries as limits for the areal dimension of the calculation. We still consider those areas and streets that lie beyond those boundaries for the individuals living near them, as long as the starting points is located within the area in question.

We are aware that with these approaches we cannot fully eliminate the MAUP, as it still relies on certain predefined parameters that can significantly affect the outcome. Walking speed, walking distance in minutes, and the buffer distance around the edges can be chosen arbitrarily and attuned to personal preferences. However, we wanted to show the general applicability of these people-centered areas and that even at this small scale considerable differences occur. We argue that with the analysis at hand, it is possible to focus on the individual inhabitants and their immediate surrounding. The resulting models are closer to the reality of individuals and thus, much more accurate as they are, compared to other reference areas, considering the physical layout of the city as experienced by actual people. One of the first avenues for future investigation is the effect of the buffer width of streets used in our IWN models. By applying our concept to cities with different urban layouts than Munich, it should be possible to determine a value that would better account for all urban characteristics and therefore make comparisons between cities feasible.

6. Conclusion and outlook

We empirically investigated the use of different reference areas on the individual level and compared them regarding their 3D density using the floor area ratio (FAR). With this we could show that it is very important to maintain a focus on the individual level, as the surrounding neighborhood can vary strongly within short distances due to artificial or natural barriers. On the basis of the IWN, this spatial concept can be used to calculate a variety of urban attributes (population density, amount of green areas, amount of amenities, etc.) that correspond to a lifelike and realistic neighborhood of the individual. Due to this tailored concept, we expect that, calculated at the spatial scale of the IWN, those urban attributes show stronger and more significant relationships with the subjective perception of the environment than has been assessed by studies up to now by using coarser spatial representations of the environment such as administrative areas or simple buffer distances. Which reference area actually coincides best with the actual perception of the citizen needs to be researched using geolocated perception data of people. Further, this offers not only new possibilities for research but also from the perspective of urban planning. In combination with micro-level socio-economic data for example, the needs and wishes of different social groups, in different social settings, can be tackled more precisely. Moreover, spatially more appropriate inter-city comparisons can be conducted in regard to specific urban attributes (e.g. available green areas) to address the health implications for each citizen. People-centered reference areas intend to better describe and understand how urban forms shape behavior and thus, how the quality of life of the urban citizens can be improved.

CRediT authorship contribution statement

Ariane Droin: Conceptualization, Methodology, Software, Formal analysis, Visualization, Resources, Writing - original draft. **Michael Wurm:** Conceptualization, Methodology, Visualization, Resources, Writing – review & editing, Supervision. **Hannes Taubenböck:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision.

References

Angel, S., Lamson-Hall, P., & Blanco, Z. G. (2021). Anatomy of density: measurable factors that constitute urban density. *Buildings and Cities, 2*(1), 264–282.

Batty, M. (2009). Defining density. *Environment and Planning B: Urban Analytics and City Science, 36*, 571–572.

Berghauser Pont, M., & Marcus, L. (2014). Innovations in measuring density: from area and location density to accessible and perceived density. *Nordic Journal of Architectural Research, 2*, 11–30.

Boeing, G. (2018). A multi-scale analysis of 27000 Urban Street Networks: Every US City, Town, Urbanized Area, and Zillow Neighborhood. *Environment and Planning B: Urban Analytics and City Science, 47*(4), 590–608.

Boyko, C. T., & Cooper, R. (2011). Clarifying and re-conceptualising density. *Progress in Planning, 76*(1), 1–61.

Bramley, G., Dempsey, N., Power, S., Brown, C., & Watkins, D. (2009). Social sustainability and urban form: Evidence from Five British Cities. *Environment and Planning A: Economy and Space, 41*(9), 2125–2142.

Bundesamt für Kartographie und Geodäsie (BKG). (2021). Dokumentation 3D Gebäudemodell Deutschland - LoD1. Available at: https://sg.geodatenzentrum.de/web_public/gdz/dokumentation/deu/LoD1-DE.pdf (accessed 30 March 2022).

Churchman, A. (1999). Disentangling the concept of density. *Journal of Planning Literature, 13*(4), 389–411.

Craig, J. (1984). Averaging population density. *Demography, 21*(3), 405–412.

Dovey, K., & Pafka, E. (2014). The urban density assemblage: Modelling multiple measures. *Urban Design International, 19*(1), 66–76.

El Din, H. S., Shalaby, A., Farouh, H. E., & Elariane, S. A. (2013). Principles of urban quality of life for a neighborhood. *HBRC Journal, 9*(1), 86–92.

European Union. (2020). Mapping Guide v6.2 for a European Urban Atlas. Available at: https://land.copernicus.eu/user-corner/technical-library//urban_atlas_2012_2018_mapping_guide (accessed 05.08.2022).

Forstall, R. L., Greene, R. P., & Pick, J. B. (2009). Which are the largest? Why lists of major urban areas vary so greatly. *Tijdschrift voor Economische en Sociale Geografie, 100*(3), 277–297.

Forsyth, A. (2003). Measuring density: Working definitions for residential density and building intensity. *Design Brief, 8*.

Gamper, J., Böhlen, M., Cometti, W., & Innerebner, M. (2011). Defining isochrones in multimodal spatial networks. In *Proceedings of the 20th ACM international conference on Information and knowledge management (CIKM '11)* (pp. 2381–2384).

Gehlke, C., & Biehl, H. (1934). Certain effects of grouping upon size of the correlation coefficient in census tract material. *Journal of the American Statistical Association Supplement, 29*(185), 169–170.

Glass, D. C., & Singer, J. E. (1972). *Urban stress: Experiments on noise and social stressors*. New York: Academic Press.

Habermas, J. (1985). *The theory of communicative action. Volume 2. Lifeworld and system: a critique of functionalist reason*. Boston: Beacon Press.

Haughton, G., & Hunter, C. (2003). *Sustainable cities*. London: Routledge.

Hofmann-Wellenhoff, B., Legat, K., & Wieser, M. (2003). *Navigation*. Vienna: Springer.

Howley, P., Scott, M., & Redmond, D. (2009). Sustainability versus liveability: an investigation of neighbourhood satisfaction. *Journal of Environmental Planning and Management, 52*(6), 847–864.

Jacobs, J. (1961). *The death and life of great American cities*. New York: Random House.

Krehl, A., Siedentop, S., Taubenböck, H., & Wurm, M. (2016). A comprehensive view on urban spatial structure: Urban density patterns of German City Regions. *ISPRS International Journal of Geo-Information, 5*(76).

Lee, S. M., Conway, T. L., Frank, L. D., Saelens, B. E., Cain, K. L., & Sallis, J. F. (2017). The relation of perceived and objective environment attributes to neighborhood satisfaction. *Environment and Behavior, 49*(2), 136–160.

Lynch, K. (1960). *The image of the city*. Cambridge: MIT Press.

McCrea, R., Shyy, T. K., & Stimson, R. (2006). What is the strength of the link between objective and subjective indicators of urban quality of life? *Applied Research in Quality of Life, 1*, 79–96.

Mouratidis, K. (2018a). Rethinking how built environments influence subjective well-being: a new conceptual framework. *Journal of Urbanism: International Research on Placemaking and Urban Sustainability, 11*(1), 24–40.

Mouratidis, K. (2018b). Built environment and social well-being: How does urban form affect social life and personal relationships? *Cities, 74*, 7–20.

Mouratidis, K. (2019). Compact city, urban sprawl, and subjective well-being. *Cities, 92*, 261–272.

Oh, K., Jeong, Y., Lee, D., Lee, W., & Choi, J. (2005). Determining development density using the Urban Carrying Capacity Assessment System. *Landscape and Urban Planning, 73*, 1–15.

Openshaw, S. (1984). *The modifiable areal unit problem*. Norwick: Geo Books.

Pafka, E. (2020). Multi-scalar urban densities: from the metropolitan to the street level. *Urban Design International, 27*, 53–63.

Plane, D. A., & Mu, W. (2021). A people-based density perspective on physical/virtual world spaces in the microcosmic city. *Land Use Policy*, 111.

Rapoport, A. (1975). Toward a redefinition of density. *Environment and Behavior, 7*(2), 7–32.

Schimpl, M., Moor, C., Lederer, C., Neuhaus, A., Sambrook, J., Danesh, J., … Daumer, M. (2011). Association between walking speed and age in healthy, free-living individuals using mobile accelerometry – A cross-sectional study. *PLoS One, 6*(8).

Sherrod, D. R. (1974). Crowding, perceived control, and behavioral after effects. *Journal of Applied Social Psychology, 4*, 171–186.

Ståhle, A (2008). Compact sprawl: exploring public open space and contradictions in urban density. *PhD thesis, KTH University*.

Stamps, A. E. (1997). Some streets of San Francisco: Preference effects of trees, cars, wires and buildings. *Environment and Planning. B, Planning & Design, 24*(1), 81–93.

Stamps, A. E. (2001). Evaluating enclosure in urban sites. *Landscape and Urban Planning, 57*, 25–42.

Stamps, A. E. (2005). Visual permeability, locomotive permeability, safety, and enclosure. *Environment and Behavior, 37*(5), 587–619.

Stamps, A. E. (2010). Effects of permeability on perceived enclosure and spaciousness. *Environment and Behavior, 42*(6), 864–886.

Taubenböck, H., Standfuß, I., Klotz, M., & Wurm, M. (2016). The physical density of the City – Deconstruction of the Delusive Density Measure with Evidence from Two European Megacities. *International Journal of Geo-Information, 5*(206).

Taubenböck, H., Weigand, M., Esch, T., Staab, J., Wurm, M., Mast, J., & Dech, S. (2019). A new ranking of the world's largest cities – Do administrative units obscure morphological realities? *Remote Sensing of Environment, 232*.

Unwin, R. (1912). *Nothing gained by overcrowding!: How the garden city type of development may benefit both owner and occupier*. Westminster: P.S. King & Son.

Weeks, J. R. (2010). Defining Urban Areas. In T. Rashed, & C. Jürgens (Eds.), *Remote Sensing and Digital Image Processing vol: 10. Remote Sensing of Urban and Suburban Areas* (pp. 33–45). Dordrecht: Springer.

Wei, Y., Huang, C., Lam, P. T. I., & Yuan, Z. (2015). Sustainable urban development: A review on urban carrying capacity assessment. *Habitat International, 46*, 64–71.

Williams, K., Burton, E., & Jenks, M. (2000). *Achieving sustainable urban form*. London: Routledge.

Wurm, M., d'Angelo, P., Reinartz, P., & Taubenböck, H. (2014). Investigating the applicability of cartosat-1 DEMs and topographic maps to localize large-area urban mass concentrations. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 7*(10), 4138–4152.

Wurm, M., Goebel, J., Wagner, G. G., Weigand, M., Dech, S., & Taubenböck, H. (2021). Inferring floor area ratio thresholds for the delineation of city centers based on cognitive perception. *Environment and Planning B: Urban Analytics and City Science, 48*(2), 265–279.

Wurm, M., Taubenböck, H., Schardt, M., Esch, T., & Dech, S. (2011). Object-based image information fusion using multisensor earth observation data over urban areas. *International Journal of Image and Data Fusion, 2*, 121–147.

Zhang, M., & Kukadia, N. (2005). Metrics of urban form and the modifiable unit problem. *Transportation Research Record, 1902*(1), 71–79.