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Assessing cities: Applying GIS-based methods for mapping cross-scale spatial indicators

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Abstract. In recent years, several systems and tools to assess energy consumption and carbon emissions at scales beyond that of merely buildings, such as LEED, CASBEE and BREEAM communities have been development. However, reviews reveal a lack of robustness in these methods both in terms of an unstructured mix of qualitative and quantitative criteria and lack of focus on urban form parameters found to influence energy consumption and carbon emissions. A promising quantitative assessment system including various urban form indicators is developed by the Urban Morphology Institute (UMI) in Paris. Within the research centre on zero emission neighbourhoods in smart cities (ZEN), a GIS-based method is applied to analyze conditions of urban form known to contribute to carbon emissions. In this paper we demonstrate how a selection of the UMI indicators describing proximity can be further specified applying GIS-based methods. The potential of applicability of urban assessment system in planning as well as design processes will increase when linked to tools that are already implemented, and map visualizations as well as data provided by these methods are highly applicable in planning and urban design. As further research, methods described in recent research within ZEN and specified measures for calculating UMI indicators, will be tested in analyses of urban development areas in Norway.

1. Introduction

> Urban stakeholders require quantitative and robust tools to implement new paths to urban sustainability. Urban form, the spatial distribution of activities and urban organization are crucial aspects of cities' sustainability. Many tools and assessment systems have been developed to improve cities' energy efficiency and environmental footprint. However, most of these tools are based on the building scale. Most urban stakeholders are now convinced that a building scale approach is not sufficient: the scale of analysis should evolve from the building to the neighbourhood, district and city scales [1, p.592].

In recent years, several systems and tools to assess energy consumption and carbon emissions at scales beyond that of merely buildings, such as LEED, CASBEE and BREEAM communities have been developed. However, reviews reveal a lack of robustness in these methods both in terms of an unstructured mix of qualitative and quantitative criteria and lack of focus on urban form parameters known to influence energy consumption and carbon emissions [2, 3]. There is still a need to develop robust tools to assess and evaluate carbon emission impacts that account for the numerous aspects of urban form that affect the energy use and carbon emission in our built-up environments. A promising assessment system including various urban form indicators is developed by the Urban Morphology Institute (UMI) in Paris [1]. In this paper we demonstrate how UMI indicators describing proximity can be further specified applying GIS-based methods.

2. Background

In recent research conducted at the research centre on zero emission neighbourhoods in smart cities (ZEN), a GIS-based method is applied to analyze conditions of urban form known to contribute to carbon emissions. Specific urban form variables related to building morphology, building densities and spatial properties of street networks are identified, mapped and analyzed in a comparative study of three design options of an urban development area in Trondheim. For each of the design options, data on population, public transport and street networks are mapped, analyzed and examined applying GIS-based methods. The analyses include various accessibility measures. Depending on the particular issue examined, proximity is measured both as “distance to” and as “amounts within distance”, applying Euclidian distances as well as distances along the street network. The defined topics were selected in order to be applicable in early phase planning, and included: closeness to retail and service, closeness to public transport (Figure 1), population density, land use diversity, street connectivity and intersection density. Results were calculated as mean values within the plan area and presented in a spider chart allowing for a comparison between the design options (Figure 2). The method reveals significant differences between the design options and seem to be highly applicable in the assessment of urban planning options to optimize urban form and reduce carbon emissions, but further research is needed to evaluate more closely which topics and measures should be included [4].

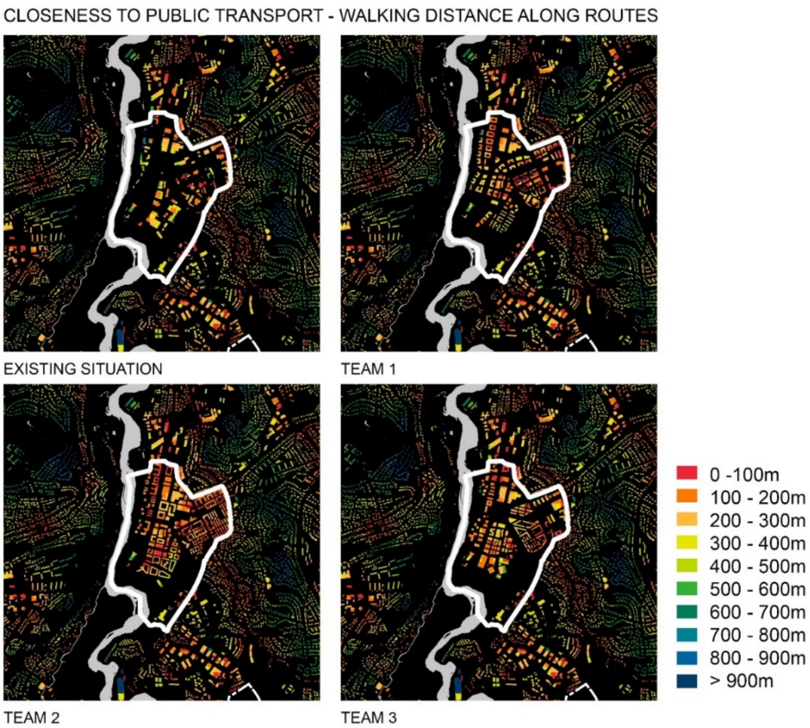

Figure 1. Maps showing results from analyses of closeness to public transport for the design options for the Sluppen area in Trondheim [4].

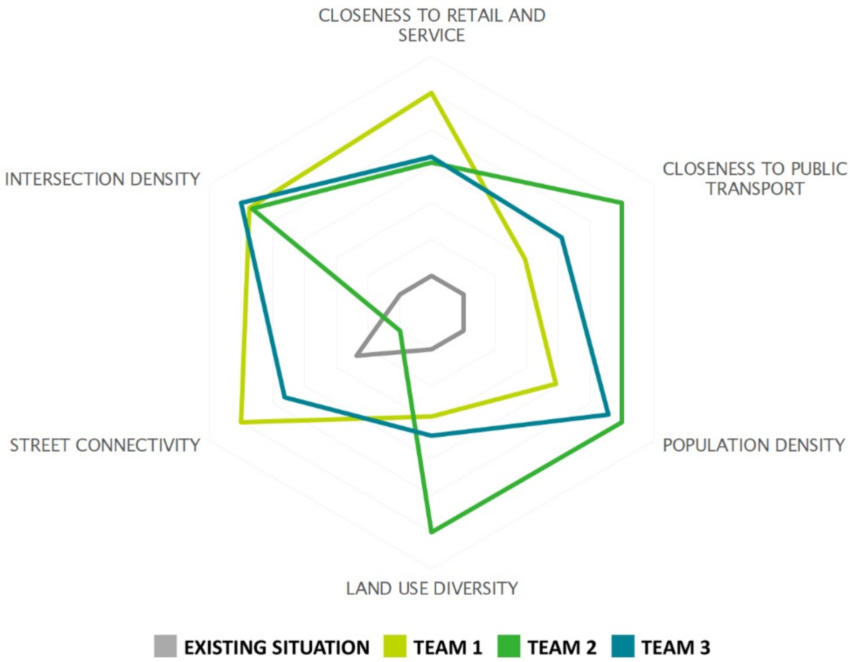

Figure 2. Spider chart of calculated mean values within the plan area for each of the topics included in the analysis of the design options [4].

An interesting approach in this respect is the work of the Urban Morphology Institute (UMI) in Paris. As a response to the lack of robustness "caused by a confusing use of qualitative and quantitative criteria" [1, p.593] in developed urban assessment systems, they propose a set of 60 quantifiable cross-scale spatial indicators for urban sustainability. They sort the indicators within the themes *land use*, *mobility*, *water*, *biodiversity*, *equity*, *economy*, *waste*, *culture/well-being* and, *energy and bioclimatic*. The indicators are further classified within seven indicator types: *intensity*, *distribution*, *proximity*, *connectivity*, *complexity*, *diversity* and *form*. Some examples of UMI indicators are:

- Human density: calculated as population per area of the selection (m^2),
- Building density, calculated as floor area (m^2) per area of the selection (m^2),
- Surface occupied by pedestrian and bicycle paths, calculated as area occupied by pedestrian and bicycle paths (m^2) per area of the selection (m^2),
- Surface occupied by road network, calculated as area of the road network (m^2) per area of the selection (m^2),
- Connectivity of the pedestrian/bike grid, calculated as the number of intersections of the pedestrian/bike grid per area of the selection (m^2),
- Cyclomatic complexity of the pedestrian/bike grid, calculated as $\mu = L - N + 1$, where L = number of links and N = number of nodes,
- Average distance between intersections in the bike/pedestrian grid,
- Proportion of the population more than 300 meters away from a public transport stop, calculated as the share of the population more than 300 meters away from public transport stop of the total population,
- Number of public transport modes accessible within 300 meters,
- Hydrological intensity, calculated as the percent of natural hydrological functions preserved or restored,
- Proportion of green fabric, calculated as green fabric area (m^2) per area of the selection (m^2),

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- Proportion of jobs in relation to housing, calculated as number of jobs per number of housings, and
- Intensity of GHG emissions per resident, calculated as GHG emissions (kg eq CO_2) per GDP [1].

In Geographical Information Systems (GIS) spatially referred or geographical data can be collected, mapped, managed and analysed, and visualized in tables and thematic maps [5]. As recent research within ZEN demonstrate, GIS allow for visual and comprehensive representation of results, and data from various scales can be extracted from the GIS model. The UMI indicators can easily be mapped in GIS allowing for visualization in thematic maps and extraction of results in various scales.

Several software extensions and plugins developed for GIS such as the ESRI network analyst and Place Syntax Tool [6] allow for network-based accessibility analyses. In this paper we will demonstrate how some of the UMI indicators can be further developed by applying GIS-based methods to measure proximity, using "amount within distance" and "distance to" applying Euclidean distances as well as distances along the street network. We present a table of the UMI indicators that can be better described and analysed applying GIS-based methods and show examples of results from analyses of some of the listed UMI indicators using the methods recently developed within ZEN.

3. GIS-based proximity measures for mapping UMI indicators

Table 1 shows a selection of UMI indicators and corresponding GIS-based measures, some of which are applied in the comparative analysis of design options for the Sluppen area in Trondheim referred to in the background section of this paper, see figure 1 and 2 [4].

Table 1. GIS-based proximity measures corresponding to UMI indicators, adapted from [1].

Theme	UMI indicator	GIS-based measure
Land Use	Human density	Residents and employees within a certain walking distance (typically 1 km)
Mobility	Proportion of the population more than 300 meters away from a public transport stop	Walking distance to public transport stop. Share of the population within specific walking distances can be extracted from the GIS model
Biodiversity	Proportion of green fabric	Share of green fabric of total area within a certain distance straight-line distance (in example shown in figure 5, the distance is set to 500 meter)
Biodiversity	Distribution of green spaces	Walking distance to green space
Economy	% of residents living less than X from a convenience store	Walking distance to convenience store. Share of the population within specific walking distances can be extracted from the GIS model
Culture/Wellbeing	Proximity of leisure facilities	Walking distance to leisure facilities. Share of the population within specific walking distances can be extracted from the GIS model

For measuring proximity indicators, input data on distance between origin and destination is required. Specifying the mode of distance is here essential. For example, for the UMI indicator *proportion of the population more than 300 meters away from a public transport stop* (by UMI calculated as the share of total population), mode of distance-measure will affect the calculated results to a high degree. Figure 2 illustrate the difference between distance modes in analyses of proximity to public transport stops in the city of Trondheim. When measuring distance as straight-line, for instance the very significant barrier effect of the river will not be grasped in the analyses, while this is accounted for in a very realistic way when measuring distance along real walkable routes. The calculated result for the UMI indicator *proportion of the population more than 300 meters away from a public transport stop* for Trondheim is 80% for the straight-line distance mode, while the share is 47% if distance is measured as walking distance, illustrating the importance of carefully choosing the most relevant mode of distance-measure.

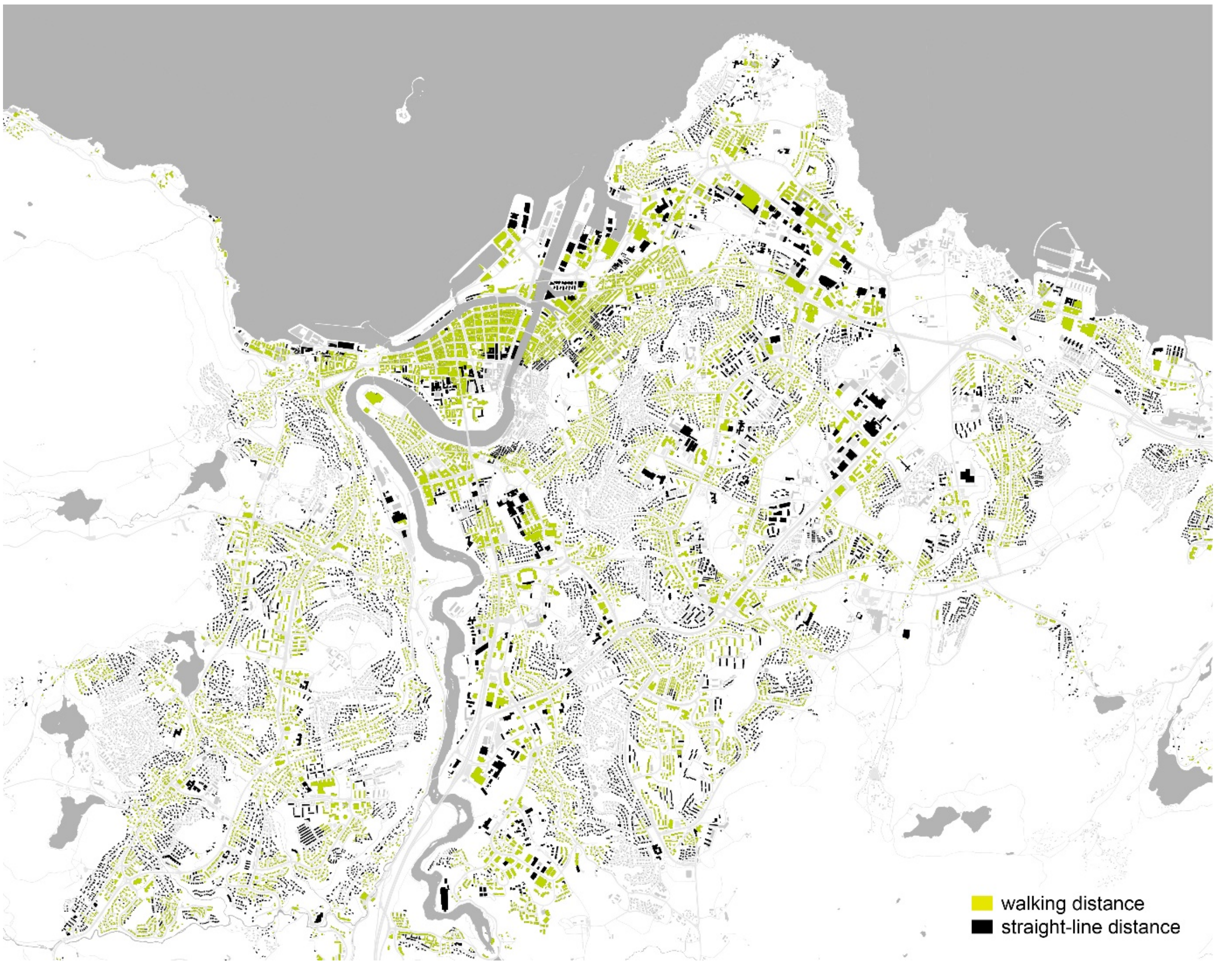

Figure 3. Map illustrating the population in Trondheim within 300 meter distance from public transport stop measuring distance as walking distance along routes (yellow). The increased share within the same distance measured as straight-line distance (black) does not afford realistic results for this specific indicator because of the very significant barrier effect of the river.

For four out of the six GIS-based measures we propose, distance is suggested measured as walking distance along route. UMI define a threshold of 300 meter distance to public transport, but for the indicators concerning proximity to convenience stores and leisure facilities thresholds are reported as X. Defining thresholds depend on what topic is addressed and what group of the population is targeted. For example, walking distance for children to playgrounds require a lower threshold compared to walking distance for active adults to leisure activities.

Figure 4 show results from analysing walking distance to convenience stores. Convenience stores are mapped manually in GIS from OpenStreetMap. The method of mapping population and street network, and of the applied analysis which is equivalent to that of the ZEN measure *walking distance* *to nearest retail cluster* is previously described by Rokseth et al. [4]. By colouring the map according to walking distances, in groups of 0-100 meters, 100-200 meters, etc., geographical areas where with high and low accessibility to convenience stores are revealed in a comprehensive way. The UMI indicator formula (share of total population) can be resolved by extracting numbers from the GIS model. As an example, in the specific case of Trondheim, the share is 1 % within 100 meter walking distance, 7 % within 200 meter walking distance, 16 % within 300 meter walking distance, and 36 % within 500 meter walking distance.

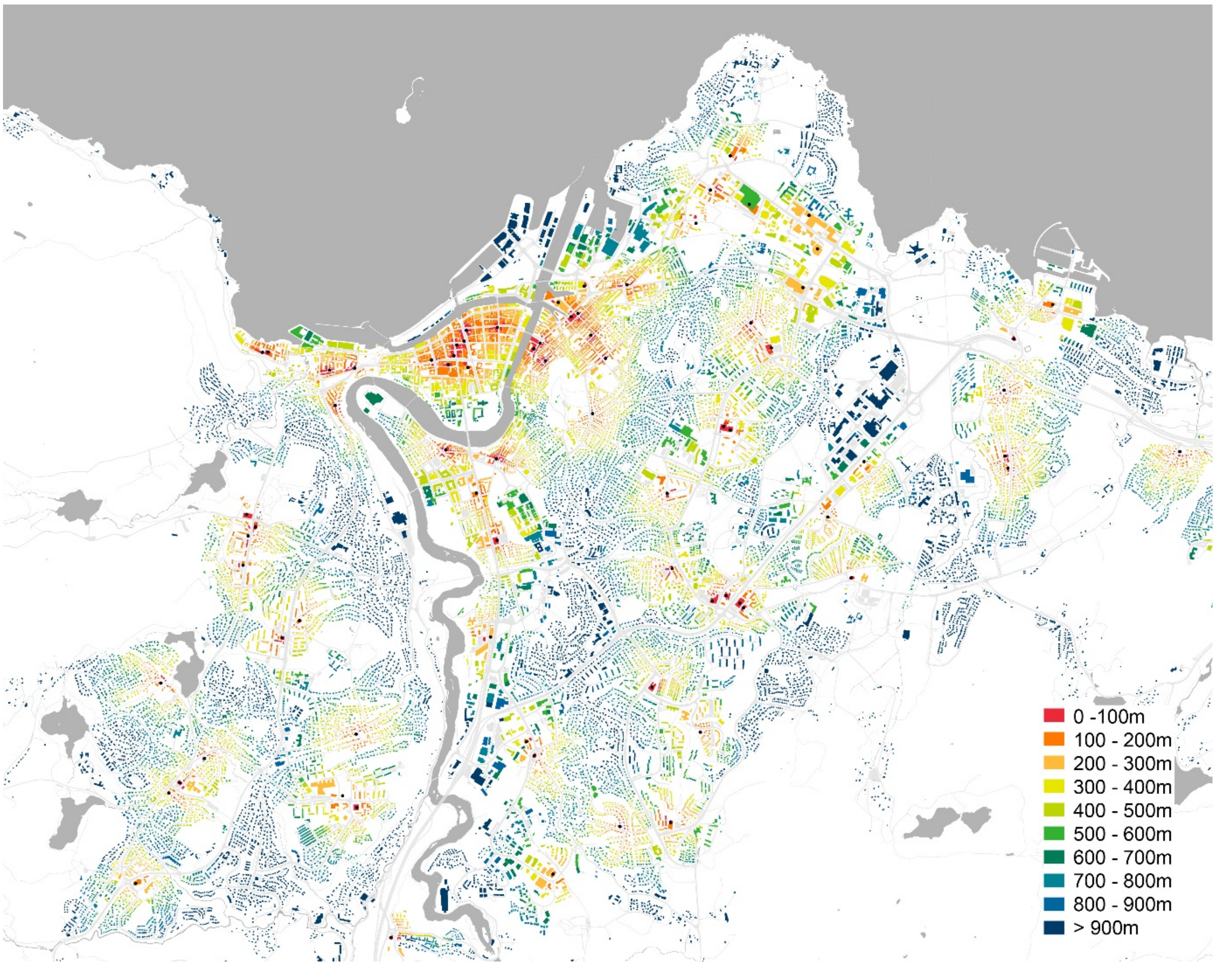

Figure 4. Walking distance from population to convenience stores in Trondheim.

Straight-line distances can be more relevant than walking distance in some cases, for example when measuring proximity from dwellings to large parks as an issue concerning availability of fresh air or the distance to motorways regarding the issue of noise and pollution. Connected to the UMI indicator *proportion of green fabric,* we propose the GIS-based measure *share of green fabric of total area within 500 meter straight-line distance*.

Input data on green fabric were retrieved form the municipality of Trondheim and included parks and recreational green spaces in several categories. Analyses were run according to procedures equivalent to the topic *land use diversity* previously described by Rokseth et al. [4], with green fabric as destination. According to UN Habitat 15-20% of the land area in "high density mixed-use urban areas" should be allocated for open public space [7, p.3]. The map in figure 5 reveal which areas that have a lower share of green than the recommendation. Out of the total population, 37% have a green fabric share of 20% or higher within 500 meter straight-line distance.

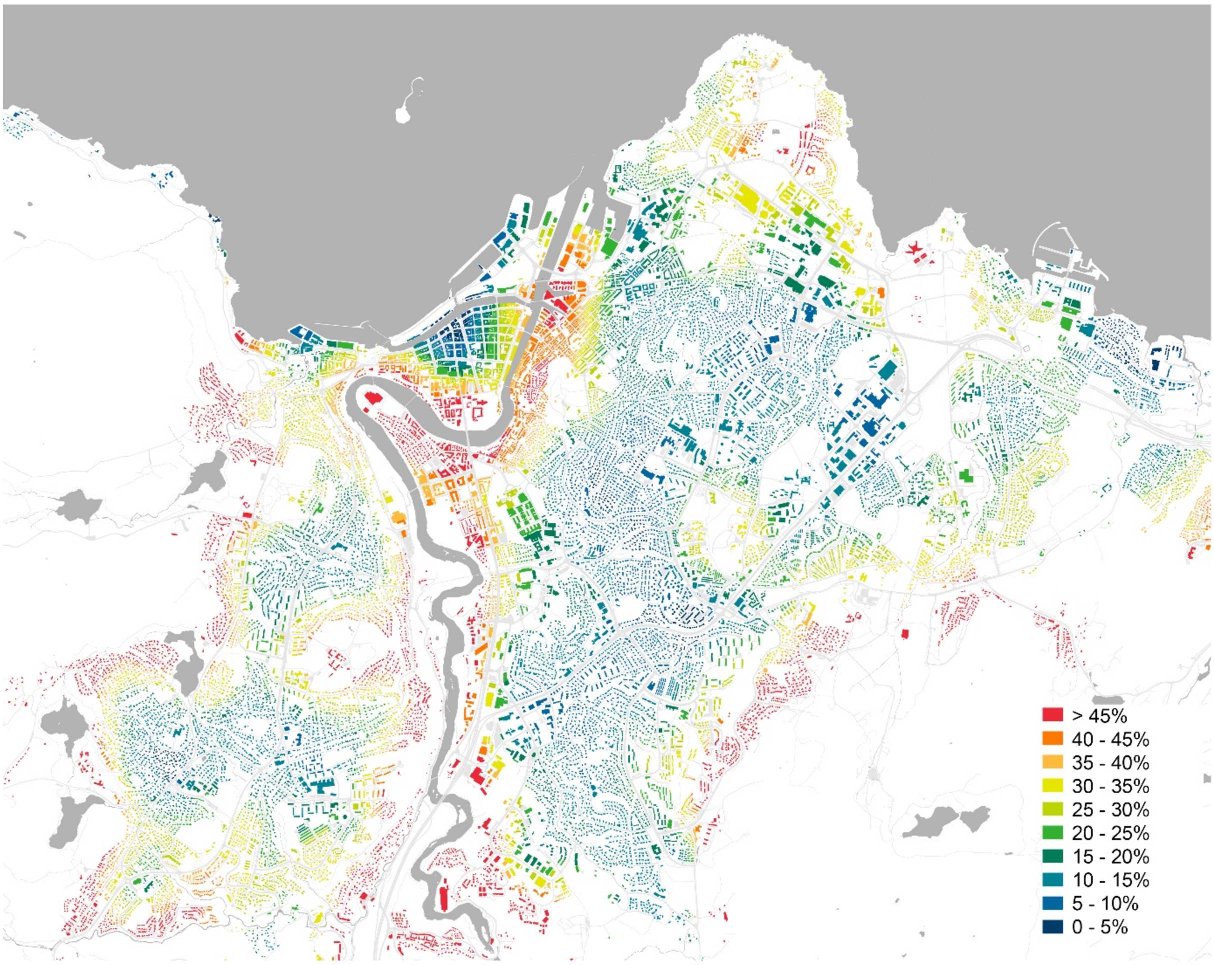

Figure 5. Share of green fabric of total area within 500 meter straight-line distance.

There are some important limitations to consider. The examples provided in this paper are analysed based on a so-called axial line map [8] representing the street network, not considering slope of the routes. Also, qualitative aspects of the street network, such as traffic safety and perceived safety and maintenance impacting route choice, are currently not grasped by the GIS model. Qualitative aspects of the green fabric will also affect whether the space will be frequented by the public. These limitations will equally apply to the UMI indicators.

4. Conclusions

GISs methods currently being developed holds a potential to support assessment systems for urban sustainability in terms of providing informative thematic maps for visualizations in different scales. In addition, GIS-based methods can be implemented to further specify which measures to apply. The GIS model will also provide data in various scales and units, allowing for several alternatives of comparing data between cities or between planning options and for a richer ground for discussions about the meaning and importance of examined topics and indicators. The potential of applicability of urban assessment system in planning as well as design processes will increase when linked to tools that are already implemented. Both map visualizations and data provided by these methods are highly applicable in planning and urban design, for instance in evaluating likely effects of alternative development alternatives as shown in the case of Sluppen.

As further research we will combine methods described in recent research within ZEN and further specify measures for calculating UMI indicators, and test these in analyses of urban development areas in Norway. Further definition of thresholds and benchmark values will be part of this work.

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