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PROPERTIES OF URBAN FORM INFLUENCING CARBON EMISSIONS

Implementing a GIS-based Method

LILLIAN ROKSETH[1]; BENDIK MANUM[2]; TOBIAS NORDSTÖM[3]

ABSTRACT

Half of the world's population currently lives in cities. While cities occupy only 3 % of the land, they account for 75 % of the global carbon emissions. Building patterns, street network design and locations of specific building functions work together in interrelated systems that have importance for both amount and modes of transport. Considerable research on urban built form related to energy use and carbon emissions have been conducted. However, this research scarcely include urban form parameters such as street network layout and building morphology as interrelated systems. Leaning on research within the field of urban form and urban morphology, as developed within space syntax research, we propose a GIS-based method to analyse conditions of urban form at neighbourhood scale that are essential to carbon emissions. For developing and testing the methods, we have identified specific urban form variables related to building morphology, building densities and spatial properties of street networks and mapped and analysed these in the case of an urban development in Trondheim, Norway. In this urban development project, three teams of architects and engineers have conducted feasibility studies resulting in concrete propositions for development of the area. The assessment method is tested in a comparative analysis of the existing situation and the three proposed scenarios. For each of the scenarios, data on population, public transport and street networks are mapped in GIS and examined by the proposed methods. Besides space syntax measures like spatial integration of the street network, the analyses include accessibility measures of several kinds. 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. By revealing significant differences between the three projects regarding variables that according to research are decisive for carbon emissions, the proposed methods seem to be highly applicable in urban planning for a sustainable future. In conclusion, the methods applied should have potential for a proceeding development of space syntax based measures in research on sustainable urban development.

KEYWORDS

Urban form, urban morphology, greenhouse gas emission, carbon emission, GIS, space syntax

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1. INTRODUCTION

The cities, today containing half of the world's population, account for 75 % of the global carbon emissions (UN, 2018). The explicit layouts of cities have impact on food provision, building operations, transportation, and distribution of goods and services, which subsequently affect energy demand and emission rates (Kellett et al., 2013; Owens, 1986). According to recent research from several approaches, urban form holds the potential to significantly reduce a city's energy consumption and carbon emissions (Baker & Steemers, 2003; Ratti, Baker, & Steemers, 2005; Salat, 2009; Steemers, 2003).

Within the field of urban morphology, studying "*urban pattern and form*" (Whitehand, 2012, p. 55), a core idea is that generic types of form (defined by principal common characteristics) relate to each other "*in a hierarchy of levels of scale*" (Kropf, 2011, p. 394). The three levels of scale were first introduced by Conzen (1960), and includes street patterns, plot patterns and building patterns (Kropf, 2011; Whitehand, 2001). A similar distinction is made by Heeling et al. (2002) which differentiate between street systems (public streets) and private islands (plots and buildings). The private islands and their surrounding streets is in combination referred to as the urban fabric, or urban tissue (Berghauser Pont & Haupt, 2010). There are several measures commonly used in urban morphology research to evaluate or describe urban form, related to the patterns of streets, plots and buildings, for example the measures of *density, diversity, distance*, *intensity, spatial distribution, proximity,* and *connectivity* (Berghauser Pont et al., 2017; Bourdic, Salat, & Nowacki, 2012).

According to Jacobs (1961, p. 446), referring to Dr. Weaver's writings about the life sciences, cities are: *"[…] problems in organized complexity [...].They present "situations in which a half-dozen or several dozen quantities are all varying simultaneously and in subtly interconnected ways […] The variables are many, but they are not helter-skelter; they are "interrelated into an organic whole"*. Considerable research on urban built form related to energy use and carbon emissions have been conducted. (For comprehensive reviews, see for example Gargiulo & Russo, 2017; Mehaffy, 2015; Rickwood, Glazebrook, & Searle, 2008; Seto et al., 2014), but most research study certain issues of the urban system separately rather than as the interrelated issues they in reality are. The majority of the research focus exclusively on CO_2 emissions in relation to either transportation or buildings, or on specific urban morphology parameters such as compactness or rate of passive volume in relation to energy consumption. We still know little about how and to what degree the interrelated properties of urban form and urban morphology such as street network layout and building morphology integrate and interact (Kellett et al., 2013).

This paper presents on-going research aiming at developing a GIS-based method used to examine urban form variables as interrelated issues in the context of optimizing urban form to reduce CO_2 emissions. Leaning on research within the field of urban form and urban morphology (Baker & Steemers, 2003; Berghauser Pont & Haupt, 2010; Bourdic et al., 2012; Ratti et al., 2005; Salat, 2009; Steemers, 2003), and based on reviewed literature on urban form in relation to carbon emissions (See for example Mehaffy, 2015; Seto et al., 2014), a set of six topics is identified and examined in a comparative analysis of three plan proposals in an urban development in Trondheim, Norway. When defining topics to examine, priority is given to the factors that according to research contribute to carbon emissions, which are density, land use mix, connectivity, and accessibility (Calthorpe, 2010; Grosvenor & O'Neill, 2014; Seto et al., 2014). In addition, our aim has been to define topics and measures that are applicable at an early planning phase. The topics included are closeness to retail and service, closeness to public transport, population density, land use diversity, street connectivity and intersection density. For each of the topics, measures are defined and analysed in the case of the urban development proposals in Trondheim, applying GIS-based space syntax methodology. Although further research will need to be carried out to evaluate more closely which measures to include in the analyses, the method presented in this paper show a potential for a broader application of space syntax based measures in research on sustainable urban development.

2. DATASETS AND METHODS

In this section we describe the proposed method in detail, presenting the topics and measures examined and how these are analysed and visualised.

2.1 Study area: Sluppen

The urban development project on which the methods are tested, is at Sluppen, 3 km south of the historical centre of Trondheim, Norway. The main highway, E6, passes through the area. The local authorities of

Trondheim, along with other major landowners, have set ambitious plans for development of the Sluppen area, and in 2017 a parallel design competition was launched with the following defined main goals:

1. Sluppen will be a part of the city with provident transport solutions following the National zero growth target, aiming at assigning all future growth in personal transport to walking, bicycling and public transport (Norwegian Ministry of Transport, 2013).

2. The area should have high density, mixed use and urban qualities providing a good environment for the residents and users of the area.

The parallel design competition resulted in concrete propositions for future development of the area from three teams of architects and engineers. These plan proposals are used as cases to examine a selection of urban form topics in the development of the GIS-based method presented in this paper. The existing situation within the same plan area is included in the analyses. Maps of the existing situation and the three plan proposals are shown in Figure 1.

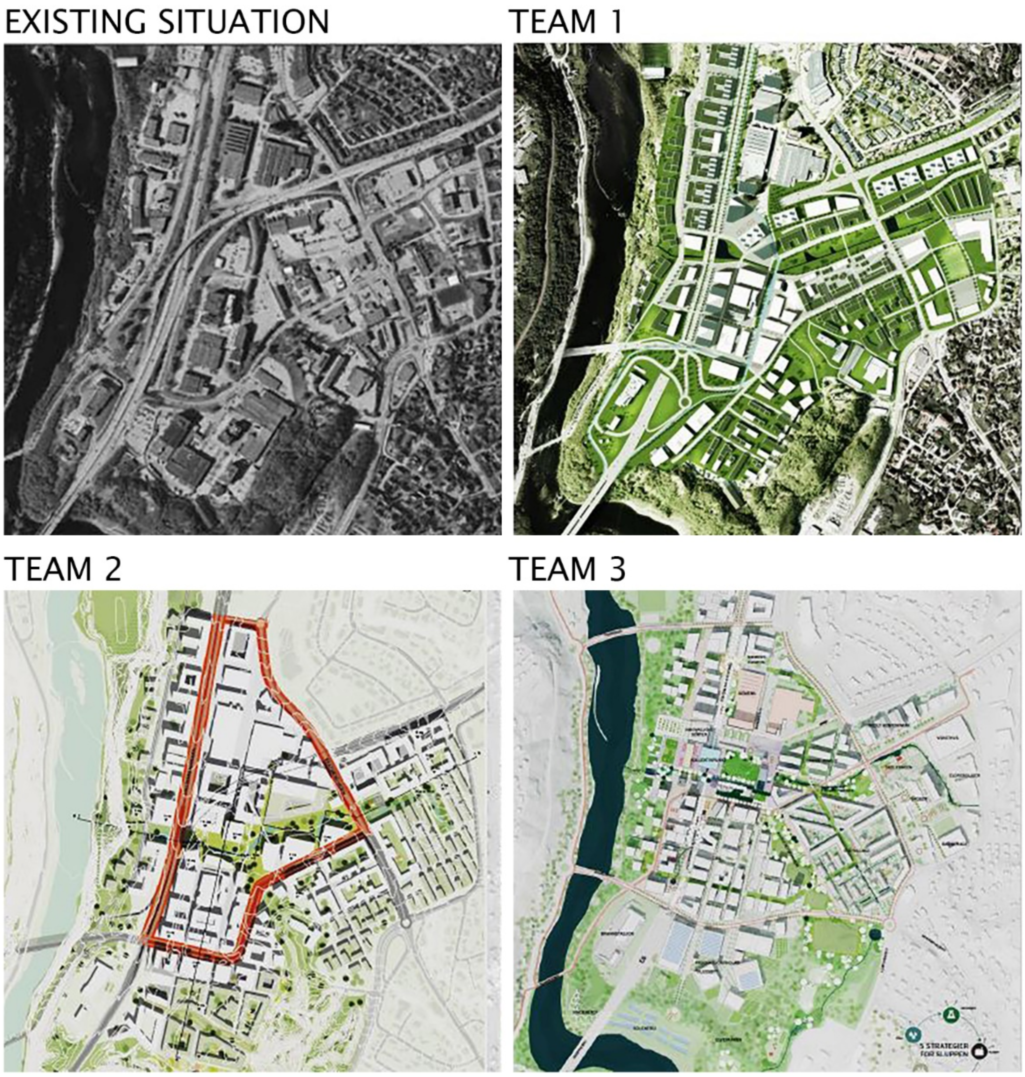

Figure 1: Maps showing the existing situation and the three plan proposals at the development area Sluppen.

2.2 Examined topics and measures

When defining topics to examine, we have prioritised the factors that according to research contribute to carbon emissions, which are density, land use mix, connectivity, and accessibility. In addition, our aim has been to define topics and measures that are applicable at an early planning phase. For example, in order to map the potential for mixed land use in the area, we have defined the topic land use diversity, which more explicitly is measured as the share of residents of the total number of residents and employees within 500m straight-line distance. Similarly, the topic closeness to retail and service measured as walking distance to nearest retail cluster/local centre serves as a proxy for mapping accessibility to explicit amenities.

The six topics included is closeness to retail and service, closeness to public transport, population density, land use diversity, street connectivity and intersection density. The topics, their connected measures and potential CO_2 impact are listed in Table 1.

Topic	Measure	Potential CO_2 impact
1. Closeness to retail and service	Walking distance to nearest retail cluster/local centre	Closeness to retail clusters or regional sub centres is, together with closeness to the town or city centre, the most important factor to explain car use (Næss, 2012; Seto et al., 2014)
2. Closeness to public transport	Walking distance to public transport stop with high level of service (< 15 min at daytime)	Accessibility to public transport increases walking and use of non-motorized travel (Ewing & Cervero, 2010; WHO, 2018)
3. Population density	Residents and employees within 1 km walking distance	Higher density increase the potential for competitive public transport and local proximity of amenities (Seto et al., 2014; UN, 2018)
4. Land use diversity	Share of residents of total number of residents and employees within 500 m Euclidian distance	For areas with a high degree of land use mix travel distances are reduced, and walking and non-motorised travel modes increases (Kockelman, 1997; Seto et al., 2014; UN-Habitat, 2014)
5. Street connectivity	Maximum Space syntax global integration within study area	A consistent positive relationship is found between utilitarian walking and space syntax integration variables (Baran, Rodríguez, & Khattak, 2008; Hillier & Iida, 2005)
6. Intersection density	Mean distance in meters between intersections for pedestrians in the street network	A strong correlation is found between intersection density and walking as chosen travel mode (Berrigan, Pickle, & Dill, 2010; Ewing & Cervero, 2010; Leslie et al., 2005; Mehaffy, 2015; Seto et al., 2014)

Table 1. Examined topics, their connected measures and potential CO_2 impact.

2.3 Data collection and mapping of existing situation in GIS

For the existing situation, shapefiles with buildings, roads, water, cencus tracts, and population data were retrieved from the Norwegian online Map Catalogue (Norwegian Mapping Authority, 2018). Due to confidentiality constraints, population data from Statistics Norway (SSB) is aggregated at a 250x250 meter grid. These data were disaggregated by assigning the residential population to residential buildings and employees to office/service buildings within each grid. Existing retail clusters including grocery stores, and functions such as post offices and pharmacies were mapped based on an overview offered by the local authorities of Trondheim (Trondheim kommune, 2012, 2017). Locations of the retail clusters were in GIS mapped as point shapefiles.

The public transport system in Trondheim is currently under development, introducing a new bus system in August 2019. Larger buses, connecting the routes of conventional buses, will service four main routes. In the GIS model, public transport stops were modelled based on data on the new transport system. The modelled public transport stops include routes with service frequency of 15 minutes or higher and average waiting time of maximum 7,5 minutes.

An axial map of Trondheim was retrieved from previous space syntax-based research conducted by NTNU and Spacescape (Manum & Nordström, 2013). This map was further developed, correcting parts of the network and adding areas of the city that was lacking. In order to calculate intersection density, a version of the axial map was converted into a polyline map which then was manually altered to fix overlapping segments in intersections.

2.4 Mapping of plan proposals

Maps of the three plan proposals were retrieved from the municipality of Trondheim as PDF files which were converted to tiff-files and georeferenced into raster layers in QGIS. Population were calculated based on provided data on building area and building function in the plan proposal files, along with historical figures (m2/person). Residential and office/service areas in the plan proposals were reported in m^2 GFA (gross floor area). These numbers were divided by a historical factor to find m^2 in GIA (gross internal area). The factor for residential buildings was set at 1,2 and at 1,5 for office and service buildings. The population count was calculated with 50m2 GIA per resident and 20m2 GIA per employee. The population were then distributed per building in the respective building category. Axial maps were drawn for each of the plan proposals, connecting the new street network within the plan area to the surrounding network. For each of the plan proposals, locations of retail clusters and bus stops were mapped in the GIS model according to details offered in the plan proposals.

2.5 Method of analysis

Analyses were run using QGIS Desktop 2.18.14 with GRASS 7.2.2/QGIS Desktop 3.4.1 with GRASS 7.4.2 (QGIS Development Team, 2019). and the Place Syntax Tool (PST) plugin version 3.0.19 (Ståhle, 2012). The topic closeness to retail and service is measured as walking distance to nearest retail cluster including basic functions such as grocery stores, post offices and pharmacies. The PST attraction distance measurement is used to calculate this, with population points as origins, axial line maps and unlink shape files as network and a point representing the retail cluster as destination. Closeness to public transport are measured using the same PST function, with public transport stops as destinations. Population density is measured as the total population (residents and employees) which reach each other within 1 km walking distance. For this topic, the PST attraction reach function is applied, defining population points as both origins and destinations, with walking distance 1km, and with results weighted by the total population count. Land use diversity is measured as the share of residents of the total number of residents and employees, which reach each other within 500 m Euclidian distance. This is calculated with the same function and defined origins and destinations as for population density, but set with a 500m Euclidian distance. Results are weighted on the total population (residents and employees) and on residents resulting in two separate columns and in a new table column, the percentage is calculated. Street connectivity is measured applying the PST network integration analysis and two separate analyses run to calculate the local integration at radii 3 (3 axial steps) and the global integration radii n (in analyses set to 1000 since n is not an optional radii in PST). In the radar chart presenting a summary of the results, the maximum integration value from the global integration analysis is used to calculate normalized scores of the topic street connectivity. Intersection density is measured as the mean distance in meters between intersections for pedestrians in the street network. This is calculated applying embedded functions in QGIS, calculating length of each polyline, summing the lengths of all included polylines and dividing by the number of polylines to get the mean value.

Basic statistics were calculated using functions embedded in QGIS. In addition, Microsoft Excel was used for supporting operations such as calculating conditional weighted mean values for the plan area and per census tract (used to sum comparable values for Trondheim city and Trondheim city centre).

2.6 Visualisations

For map visualisations of the topics closeness to retail and service, closeness to public transport, population density and land use diversity, the results were transferred to an analysis grid by intersect and joining operations in QGIS. Additional basemaps and mask layers were then added to the GIS model.

For summing and visualisation, the result values from the analyses were converted into standardized scores in the range (0, 1) through a unity-based normalization process:

$X' = (X - X_{min})/(X_{max} - X_{min})$

Where X is the variable to be normalized, X' is the normalized score of the variable, and $X_{max} - X_{min}$ is the maximum and minimum value in the data range to be normalized. In the case of closeness to local centre and closeness to public transport stop, where low values are favourable, the formula is reversed: $X' = 1- (X - X_{min})/(X_{max} - X_{min})$. The normalized scores for all analyses are presented in a radar chart, including the three plan proposals, the existing situation within the plan area. The score for Trondheim city centre, calculated relative to the score range of the four alternatives within the plan area, is also included in the radar chart.

3. RESULTS

Results from the analyses are first presented separately for each of the examined topics in maps (Figure 2-6) and column charts (Figure 7). The new plan proposals are presented next to the existing situation within the plan area Sluppen. As comparison, the mean values for Trondheim city is shown in the column charts for the topics closeness to retail and service, closeness to public transport, population density and land use diversity. The mean value of the city centre serves as comparison in the column charts for the topics street connectivity and intersection density.

Next, we present a summary radar chart based on normalized scores for all of the six examined topics (Figure 8). All four alternatives within the plan area are included in the chart, which in addition include the scores of the city centre as comparison.

3.1 Topics examined separately

In all three plan proposals clusters of service buildings are defined at a centralized location within the plan area, and this decrease the mean value walking distances compared to the existing situation where the local centre have a more decentralized location. While the mean value of the existing situation measured within the plan area is 801 meters, the mean values lie within a range from 365 to 531 meters for the plan proposals.

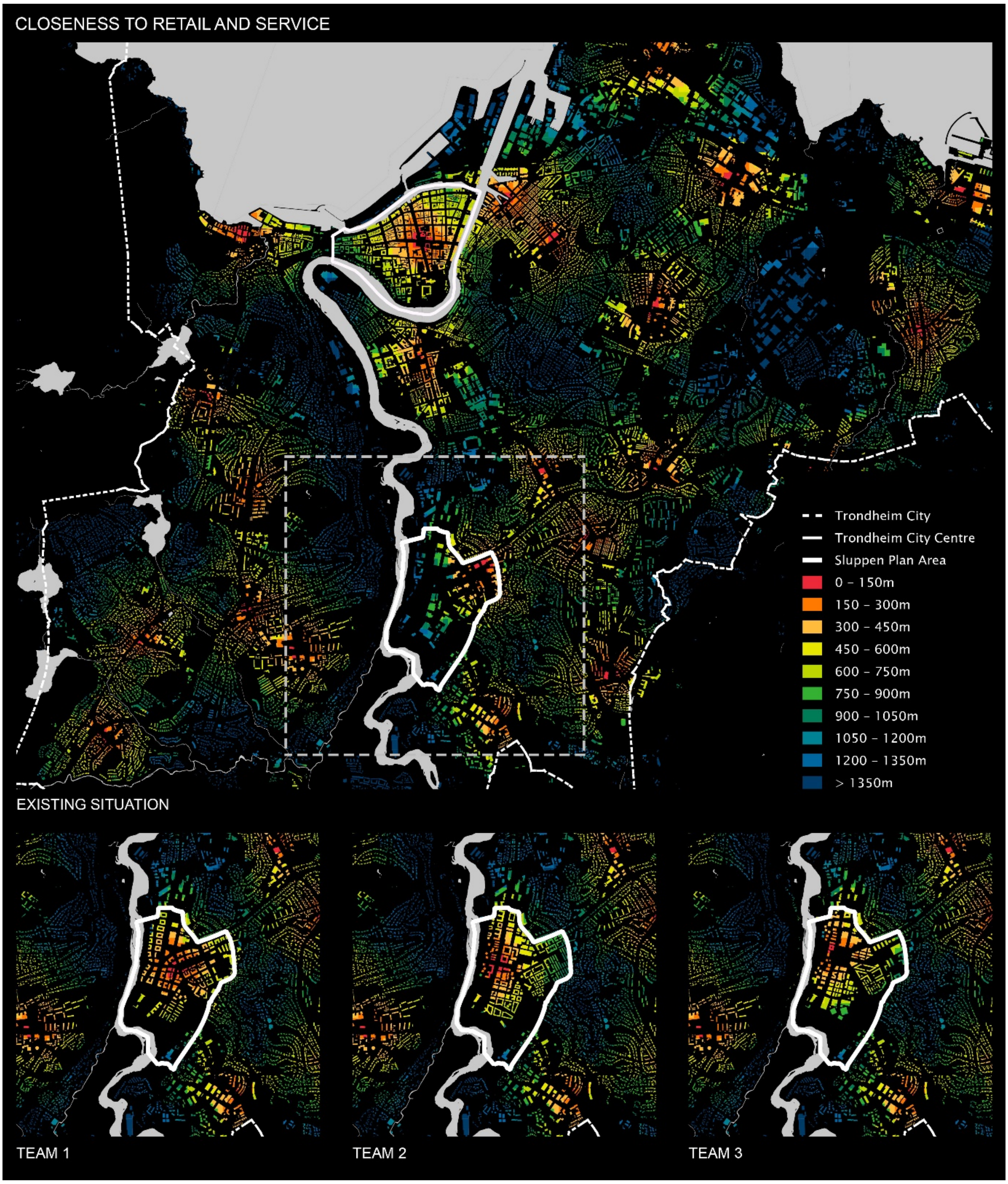

Figure 2: Closeness to retail and service measured as walking distance to nearest retail cluster/local centre.

Mean walking distances to public transport within the plan area decrease for all plan proposals compared to the existing situation. While the mean value for the existing situation within the plan area is 369 meters, the values for the plan proposals vary from 210 to 307 meters.

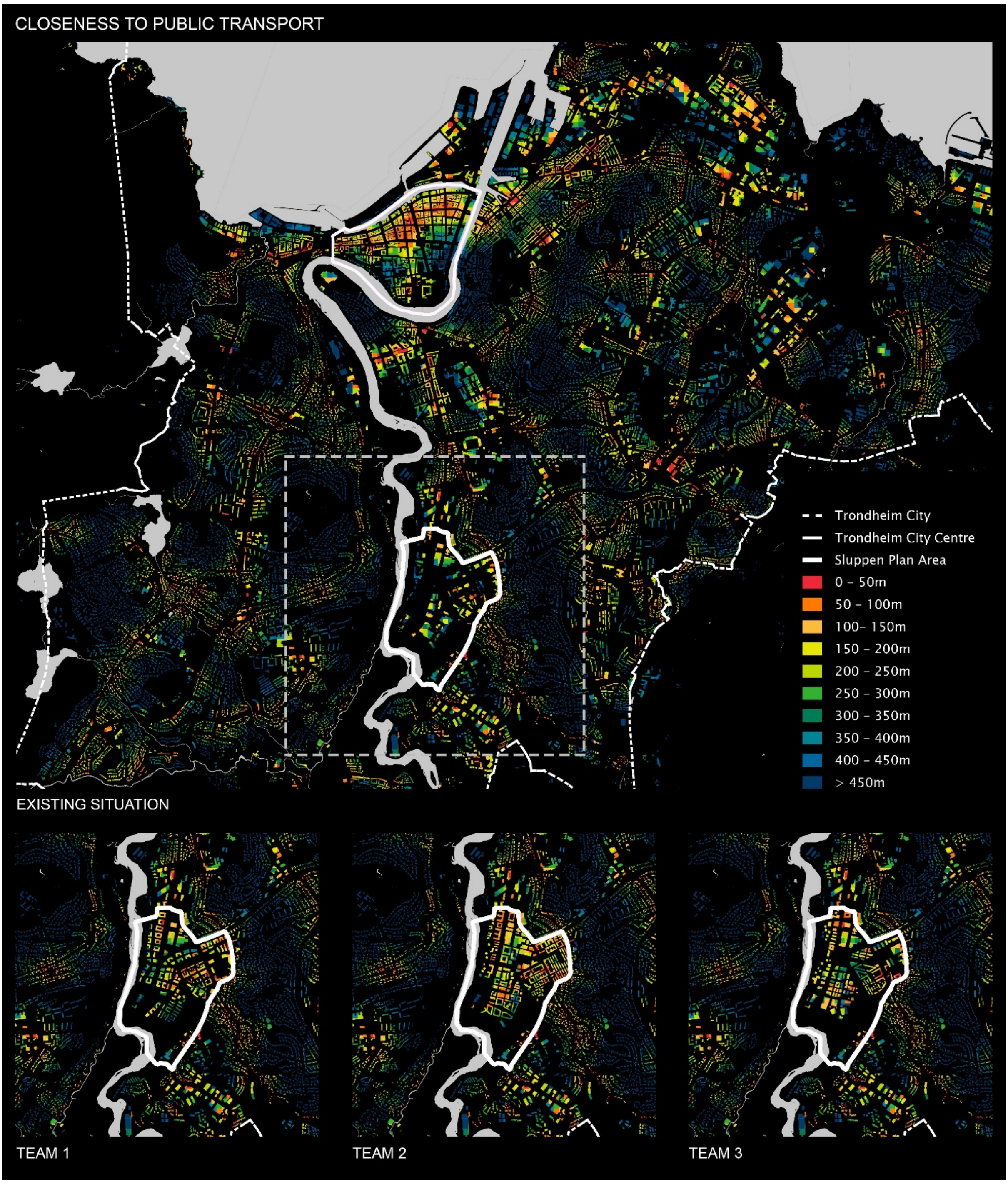

Figure 3: Closeness to public transport stop measured as walking distance to public transport stop with high level of service (< 15 min at daytime).

All plan proposals increase the population density compared to the existing situation within the plan area, but the density vary to a high degree between the plan proposals. Mean values for the proposals vary from 16391 at the lowest to 24138 as the highest. In comparison, the densest populated area in Trondheim, the inner city, have a mean value of 25724. Maps visualising the population density for the existing situation and the plan proposals is shown in Figure 4.

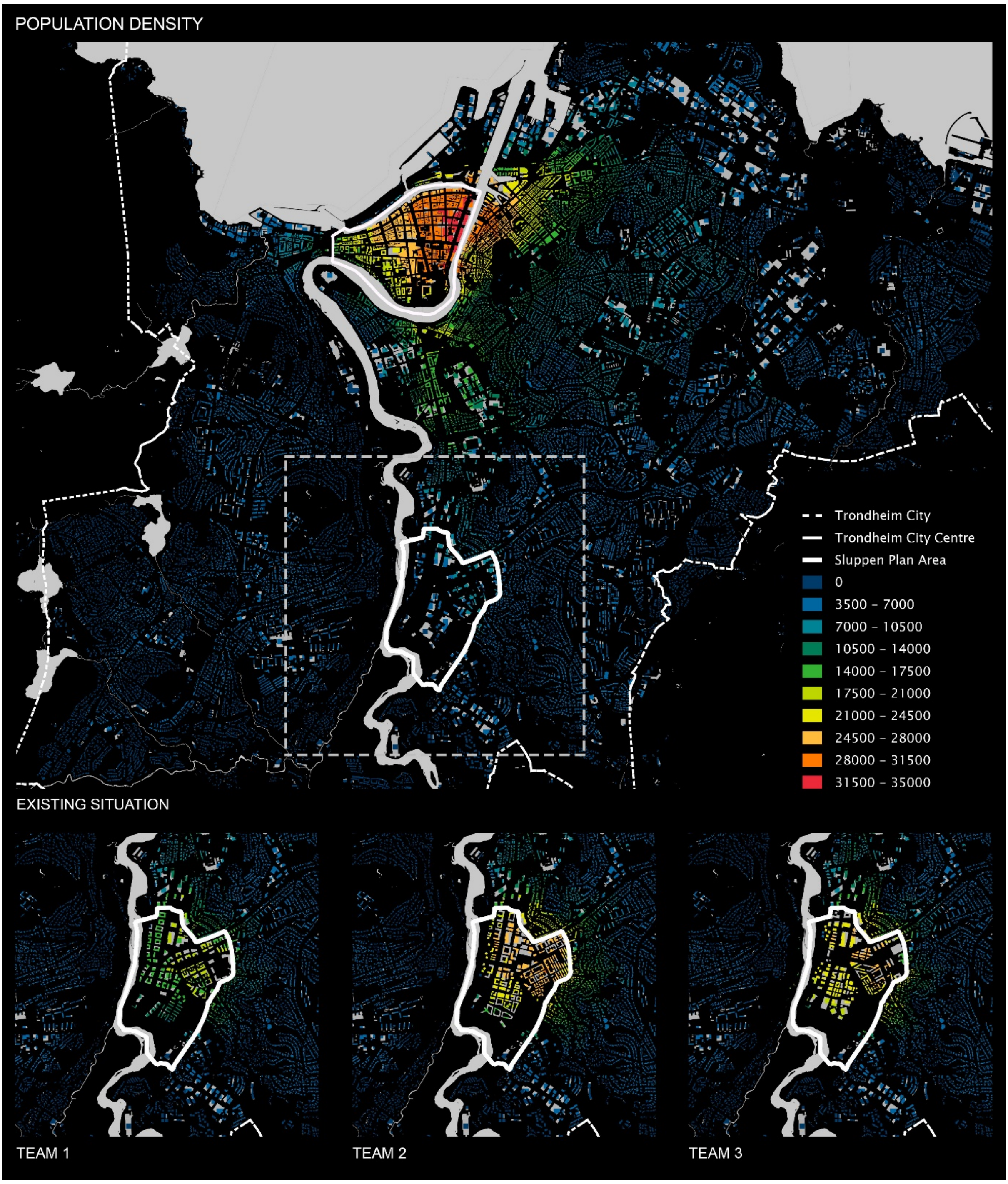

Figure 4: Population density measured as residents and employees within 1 km walking distance.

Land use diversity is in this paper calculated as the share of residents of the total population (residents and employees). Industry and offices currently dominate at Sluppen, and this is reflected in the mean value of 12 % residents of the total population for the existing situation. For the plan proposals, the shares lie within a range of 19% and 31%. In comparison, Trondheim city centre has a share of 22%, while the share is 71% for Trondheim city. The map in Figure 5 visualising the existing situation illustrate how some parts of the city are dominated by residents whereas other parts have a high share of employees.

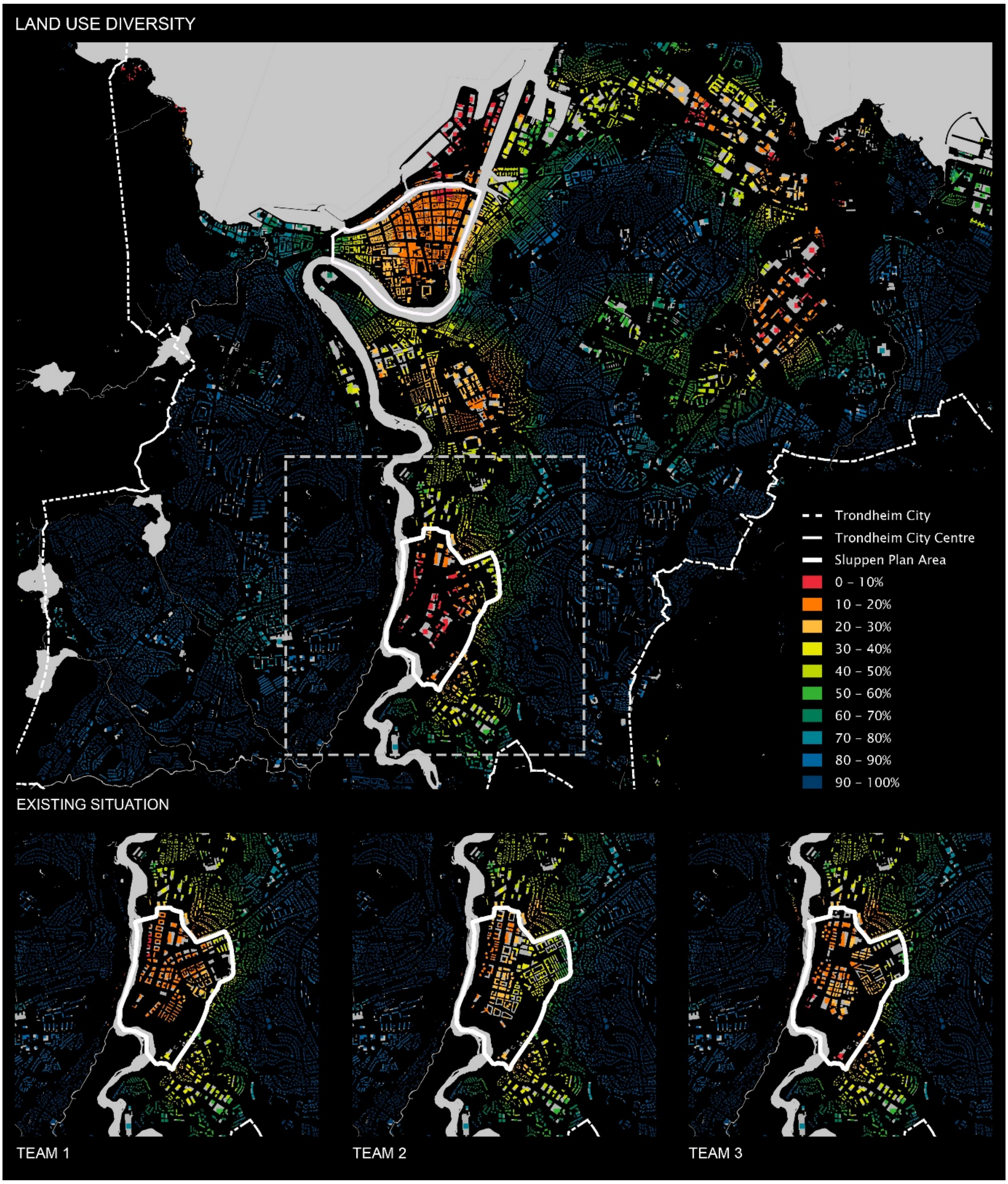

Figure 5: Land use diversity measured as share of residents of total number of residents and employees within 500 m Euclidian distance.

In Figure 6, street connectivity is visualised as space syntax global spatial integration calculated with the Place Syntax Tool (PST) with the radii set to 1000 (since n is not an option in the calculation). The maximum integration values within the plan area for all alternatives are used to compare the existing situation and the three plan proposals in the column chart in Figure 7. For all plan proposals, the integration values increase compared to the existing situation. Team 3 is the alternative with the highest maximum integration value (Team 3), which is also reflected in the map of global spatial integration (see Figure 6).

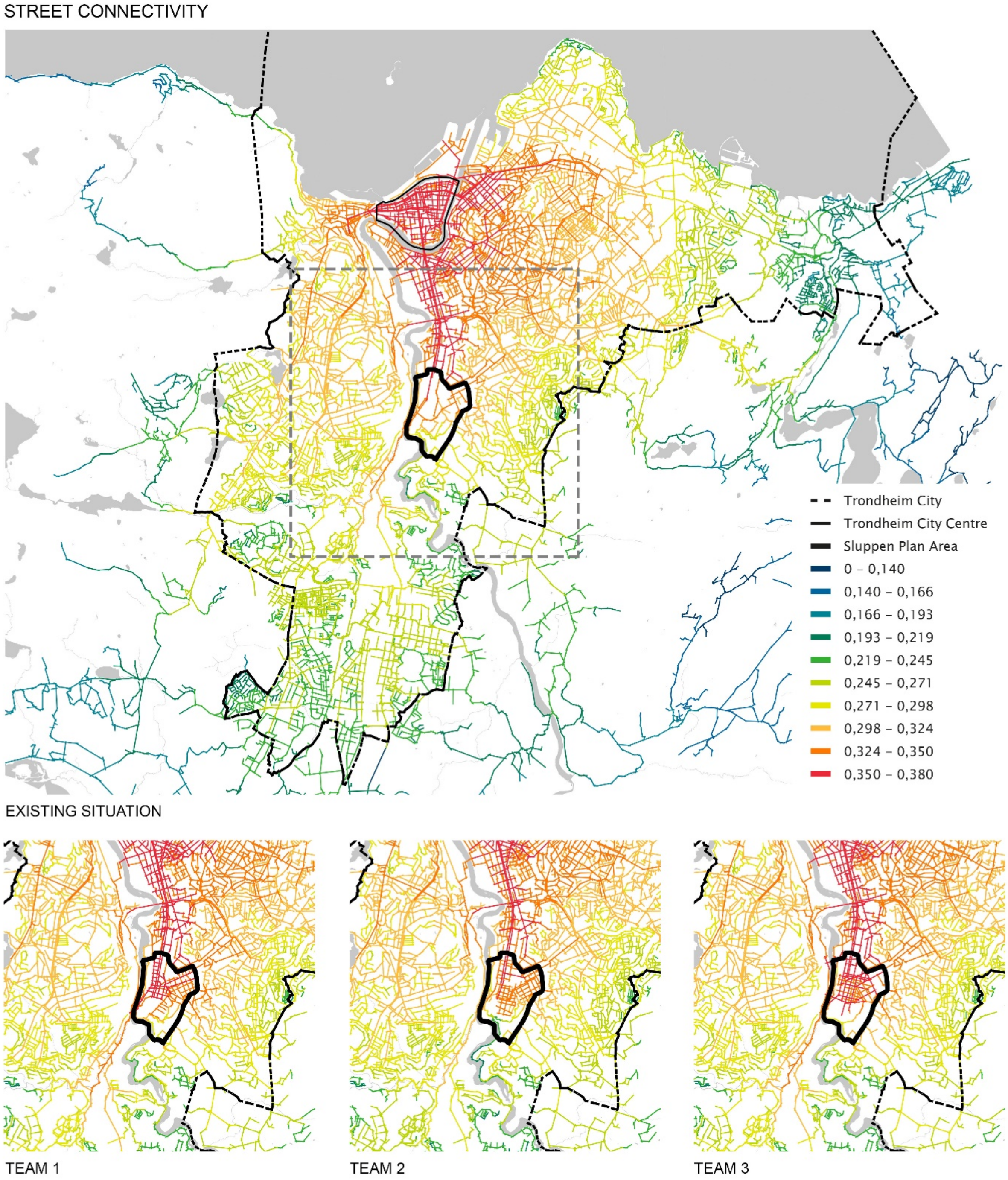

Figure 6: Space syntax global integration.

The mean distance between intersections is for the existing situation within the plan area 222 meters, while for the plan proposals the value vary from 72 to 82 meters. In comparison, the mean distance between intersections in city centre is 66 meters.

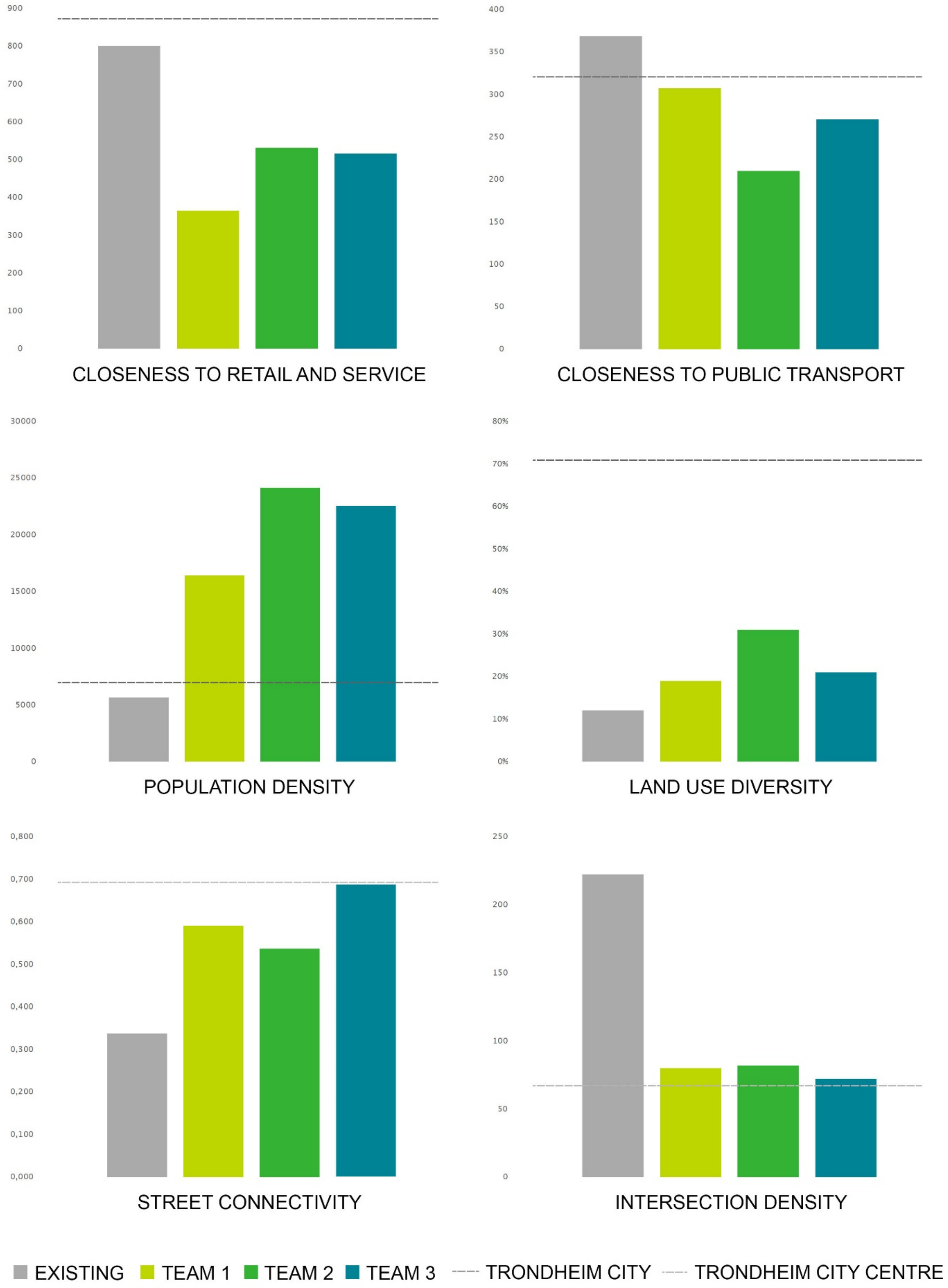

Figure 7: Mean values of each topic within the plan area for the existing situation and the three plan proposals, and comparable values of Trondheim City and Trondheim City Centre.

3.2. Variance between the plan proposals comparing normalized scores

By normalizing the results within each examined topic, it is possible to compare how the different plan proposals perform relative to each other and in relation to the existing situation, within the plan area and in the city center.

Figure 8 show a radar chart of the normalized scores for each of the examined topics. The scores for Trondheim inner city are included as comparison and these are calculated relative to the normalized scores of the four alternatives within the Sluppen plan area. For five of the six analysed topics, the existing situation within the plan area gets the lowest score, which means that when comparing these topic measures, the situation for these five topics improves in all plan proposals. For the topic closeness to retail and service, Team 1 is significantly better than the other plan proposals. Team 2 has the highest scores in 4 of the 6 topic measures; closeness to public transport, population density, land use diversity and intersections density. In the radar chart presenting a summary of the results, the maximum integration value within the plan area from the global integration analysis is used to calculate normalized scores for street connectivity.

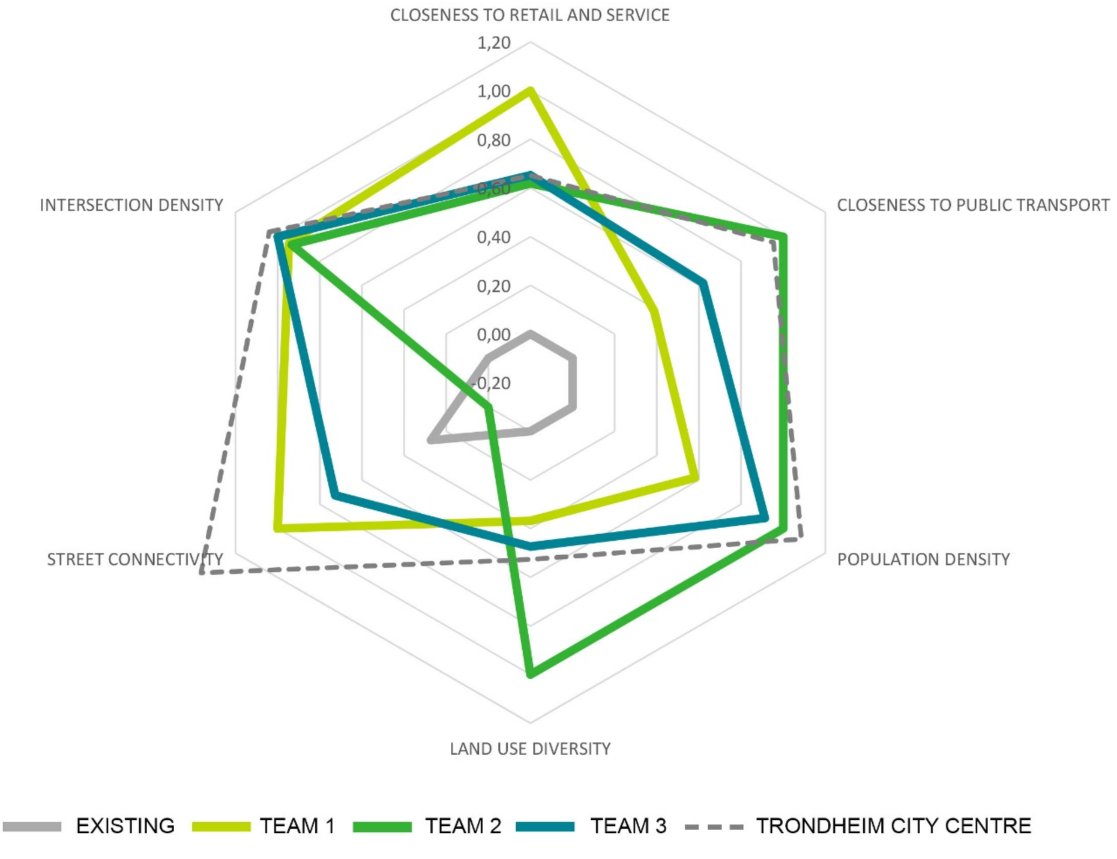

Figure 8. Radar chart showing normalized scores of the examined topics.

4. DISCUSSION

In this section, we address the relevance of the defined topics and measures examined in this paper, the reliability and precision of data used in the analyses and the need for further development of the method in terms of defining benchmark values and prescriptive ranges to evaluate planned proposals for developments.

4.1. Relevance of defined topics and measures

Some of the topics and measures presented in this paper should be more specified to be applicable in real early phase planning. This especially apply to the topic closeness to retail and service; In this paper retail clusters are mapped as geographical points in locations defined by the local authorities. As now mapped, the problem of car based shopping centres is not grasped by the method. Closeness to the city centre is a topic of high relevance when it comes to modes of transportation and carbon emission (Ewing & Cervero, 2010), but this is not addressed in this paper since the distance is constant for all plan alternatives. Closeness to city centre and closeness to retail and service both serves as proxies for mapping explicit destinations, attractions and amenities. Rather than defined clusters of retail/local centres, the measure should be to a set of defined destinations or attractions, these being located in a shopping mall or distributed within the urban fabric of the city. Destinations and attractions should include functions such as grocery stores, cafés/restaurants, and pharmacies.

In the case of closeness to public transport, the measure could be developed further taking into account time estimated per travel and not merely walking distance to the bus stop. Potential measures to examine further could be for example minutes by public transport including time used for walking to and from bus stop. In Trondheim, bus is the only public transport type available with high level of service and, since frequencies and service of bus routes can easily be changed, closeness to public transport will to some extent still be an unpredictable variable.

Within space syntax methodology, measures of connectivity and betweenness affect the accessibility and walkability in a city. We believe that there are possibilities for a broader application of space syntax measures in research on sustainable urban development. For instance, a consistent positive relationship has been found between utilitarian walking and space syntax integration variables (Baran, Rodríguez, & Khattak, 2008; Hillier & Iida, 2005). In this paper, the topic street connectivity is calculated as the maximum global integration value within the Sluppen plan area. Further research is needed to identify which measure that best represent the relationship between network integration and walkability in the specific case of Trondheim.

4.2. Reliability and precision of data

In the current version, the population estimation for the plan proposals is based on simplified schemes for ratios where population counts are calculated based on reported GFA (gross floor area) in the plan proposals. This should be kept in mind when interpreting the results, and hence the indifferences between existing situation and the plan proposals will not be accurate. This affects the precision of all measures that include population origins and/or destinations. It also affects the analysis of population density and land use diversity. Also, since there were different definitions of building functions in the different plan proposals, there is a potential that data may have been wrongly interpreted and mapped. To reduce this kind of uncertainty and to facilitate for fair comparison, the plan proposals should have reported built area in mutually defined categories, for example residential, office, service and public. Ideally, they should also have included estimates of number of apartments.

4.3. Benchmark values needed to evaluate results

Further work is needed to define benchmark values for the topics addressed in this paper. For example, international benchmark values on population densities are not necessarily applicable to cities the size of Trondheim. For several of the analysed topics walking distance is the result output. Prescriptive ranges on walking distances can vary according to which topic is examined. Recommended walking distances also depend on which group of the population is targeted in the analyses (e.g. walking distance for children to school building).

For several of the measures described in this paper, a high score is favourable. However, when addressing population density, it is important to bear in mind that there are also limits to how dense an area should be in order to be liveable and attractive. For the measure of land use diversity, neither the lower part of scale (low mix of uses due to mainly workplaces, red colour in figure 5) or the upper part of the scale (low mix of use due to mainly dwellings, blue colour in figure 5) would be favourable to achieve “attractive or vibrant urban life”. According to UN-habitat (2014) the favourable mix are the ranges giving 40-60% floor area for economic use and 30-50% for residential use. In addition, 10% of the floor area should be allocated for public services.

5. CONCLUSIONS

This paper presents on-going research on GIS-based methods developed to examine urban form variables as interrelated issues in the context of optimizing urban form to reduce CO_2 emissions. The further research will evaluate more closely which measures to include in the analyses. This will be done by comparing a set presumably significant measures to empirical data on carbon emissions per area and by capita, and by data on travel habits such as modal shares of daily commuting.

A set of benchmarks or prescriptive ranges will be proposed. Although the analyses now include only a limited set of measures, the current version of the method is applicable in evaluating planning proposals in an early planning phase.

So far, our research has focused on measuring and comparing urban form variables that according to research are decisive for carbon emission. Besides proceeding in developing the spatial measures and comparing these to empirical data as mentioned in previous paragraph, future research will include more detailed inquiries on the relationships between each variable and explicit emissions. By this, the measures and the method presented in this paper should have potential for contributing in the development of space syntax based thinking in research on sustainable urban development.

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