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Using connectivity for measuring equity in transit provision

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ABSTRACT

This study proposes the assessment of equity in transit provision by using transit connectivity as a comprehensive impedance measure. Transit connectivity considers in-vehicle time, access/egress times, waiting time, service reliability, frequency, and 'seamless' transfers along multi-modal paths. In addition, transit connectivity weighs the impedance components according to their relative importance to travelers. The assessment of equity was performed for the multi-modal transit system in the Greater Copenhagen Area, renowned for its transit-oriented finger-plan. The assessment method used a GIS representation of the network (i.e., service lines, timetables, metro stations, train stations, and bus stops), and transit assignment results (i.e., level-of-service times, passenger flows). The assessment method proved effective in calculating location-based and potential-accessibility measures and Gini coefficients of inequality in the Greater Copenhagen Area. Results show that the transit-oriented development contributes to spatial equity with high connectivity in densely populated zones, vertical equity with comparable connectivity in high income and low income zones, inter-generational equity with good connectivity provision for students to higher-education and job opportunities. Also, results show that the north-west 'finger' is less equitable with lower connectivity for low population density and lower connectivity to higher-education opportunities regardless of the high number of students.

1. Introduction

The last decades are witnessing a slow but steady paradigm shift from planning 'mass transit' to considering equity and social inclusion as an integral part of the transit planning process. While equity and social inclusion have been initially discussed with respect to fare policies, concessionary fares, and transit subsidies, the perspective has been widened to include population groups with mobility limitations (Ferguson et al., 2012). Most recently, the need for systematically incorporating spatial, temporal and socioeconomic distributional effects in transport decision-making has been discussed (Jones and Lucas, 2012).

The interest in considering equity and social inclusion was first manifested during the 1990's by discussing the need to integrate equity as a policy goal in transport provision (Masser et al., 1992; Gudmundsson and Höjer, 1996). Since the beginning of this millennium, this interest is reflected in the nascence of three main research streams. The first stream describes links between transit provision, time-poverty, social exclusion, and well-being, for both the general (Currie and Delbosc, 2010), disabled (Lubin and Deka, 2012), female (Matas et al., 2010), and low-income (Cebollada, 2009; Lucas, 2011) population. The second stream proposes conceptual frameworks to incorporate equity assessment within transport project appraisal (Martens, 2011; Martens et al., 2012; Thomopoulos and Grant-Muller, 2013). The third stream focuses on integrating equity impact assessment in transit planning and transit appraisal (Ferguson et al., 2012; Monzón et al., 2013). The current study pertains to this third stream.

Equity assessment is the connecting thread across the three lines of research and closely relates to accessibility measurement. Equity is broadly defined as the level of fairness in the distribution of benefits. Transport equity is generally categorized as horizontal equity, concerning the fairness in the distribution of impacts between individuals and groups considered equal in ability and need, and vertical equity, concerning the equality in the distribution of impacts between individuals and groups that differ in abilities and needs (Litman, 2002). Accessibility is broadly defined as the ability and ease of reaching activities, opportunities, services and goods, and accessibility gaps are defined as the differences in accessibility across geographical areas, population groups, and time. These accessibility gaps serve as indicators for identifying spatial, vertical, temporal, and inter-generational inequities (Martens et al., 2012). The definitions of accessibility and the

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classification of infrastructure-based, location-based, gravity-based, person-based and utility-based accessibility measures are extensively reviewed by Geurs and van Wee (2004).

In the transit context, equity assessment often relies on infrastructure-based measures that typically include calculating the population within distance bands from stops by service type, the number of stops by census tract or traffic zone, and the distance to the nearest stop by non-motorized modes. Infrastructure-based measures can be weighted by service capacity and frequency (Delbosc and Currie, 2011; Jaramillo et al., 2012), but their main disadvantage is that they measure the accessibility to the transit system rather than between origins and destinations. For this reason, infrastructure-based measures are typically combined with location-based measures, which consider the impedance between origins and destinations, and potential-accessibility measure, which consider the joint effect of impedance and zone attractivity. Recently, spatial equity (Delmelle and Casas, 2012; Mavoa et al., 2012; Mamun et al., 2013; Monzón et al., 2013), vertical equity (Bocarejo and Oviedo, 2012; Foth et al., 2013) and inter-generational equity (Foth et al., 2013) in transit provision were assessed via potential-accessibility measures. The investigated systems were bus rapid transit (BRT) (Bocarejo and Oviedo, 2012; Delmelle and Casas, 2012), buses (Mavoa et al., 2012; Foth et al., 2013; Mamun et al., 2013; Welch and Mishra, 2013), trains (Mavoa et al., 2012; Foth et al., 2013; Monzón et al., 2013; Welch and Mishra, 2013), and ferries (Mavoa et al., 2012). The impedance measure between origin and destination zones was the travel time calculated from commercial speeds for BRT and trains (Bocarejo and Oviedo, 2012; Delmelle and Casas, 2012; Monzón et al., 2013), and official schedules for buses (Mavoa et al., 2012; Foth et al., 2013; Mamun et al., 2013). The travel time components mostly used for the analysis were in-vehicle time, access/egress time and waiting time, while transfer times were seldom used (Foth et al., 2013; Monzón et al., 2013). These studies presented severe limitations in focusing mainly on travel time, disregarding the different preferences for travel time components, ignoring the probabilistic nature of path choice, overlooking travel time reliability, and calculating equity measures at levels other than spatial.

This study proposes the assessment of equity in transit provision by using transit connectivity as a comprehensive impedance measure, calculating location-based and potential-accessibility measures based on this measure, and computing a Gini coefficient that provides an equity measurement. The proposed assessment method allows overcoming severe limitations of previously applied methods based on accessibility measures. Firstly, the proposed method measures equity while shifting the focus from travel time to a comprehensive measure of in-vehicle time, passenger discomfort associated with waiting, transfer and access/egress times, service reliability and frequency, and "seamless" transfers along multi-modal paths with specified travel demand. Secondly, the proposed method evaluates equity while accounting for differences in the perceived discomfort of passengers for the different time components (Raveau et al., 2011; Anderson et al., 2013). Thirdly, the proposed method assesses equity while considering time variability given the increasingly recognized importance of travel time reliability for passengers as a key objective in transit operations (Ceder and Teh, 2010; Carrasco, 2012). Fourthly, the proposed method evaluates equity while recognizing that in multi-modal transit systems there exist numerous options per origin–destination pair as transit path choice is probabilistic (Raveau et al., 2011; Anderson et al., 2013). Lastly, the proposed method calculates equity while computing a Gini coefficient that allows for considering different levels of equity and different areas of the public transport system with the aim of suggesting possible locations for intervention.

This study applies the proposed method to the multi-modal transit system in the Greater Copenhagen Area (GCA), renowned for its transit-oriented finger-plan for urban development (for an extensive review, see Knowls, 2012). The data consisted of the GIS representation of the multi-modal network including metro, trains, and buses, and detailing service lines, timetables, and stations. Origin–destination travel demand matrices provided information about the current use of the network, and estimates regarding the importance of the travel time components were obtained from the Danish National Transport Model (LandsTrafikModel, LTM). Zone level data were available regarding zone size, population and socioeconomic characteristics. Transit connectivity was calculated for each origin–destination pair by modifying the algorithm proposed by Ceder (2007), which was previously applied to simplified bus (Ceder et al., 2009; Ceder and Teh, 2010) and water transport networks (Ceder and Varghese, 2011), in order to accommodate multiple paths per origin–destination pair in the complex multi-modal network. Notably, the current study is the first to apply transit connectivity to a large-scale GIS-based metropolitan size network. Location-based and potential-accessibility measures were calculated from the transit connectivity for the zones within the GCA, and maps of their distributions were compared to the maps of the distributions of population characteristics to provide visual comparison of possible gaps in connectivity and hence assess equity. The assessment concerned spatial equity (i.e., fairness with respect to the spatial distribution of opportunities), vertical equity (i.e., equality with regard to groups with different socioeconomic characteristics), and intergenerational equity (i.e., fairness in relation to younger generations having opportunities for reaching equality in the future with respect to the current adult generations). Gini coefficients were computed for the entire study area as well as for sub-areas in the transit-oriented finger-plan to provide a measure of the gaps in equity and suggest possible areas for intervention.

The paper is structured as follows. Section 2 presents the methodology applied in this study by providing details about transit connectivity, location-based and potential-accessibility measures. Then, Section 3 introduces the case study with the description of the study area, the transit network and the multi-modal transit services. Last, Section 4 presents the results and Section 5 draws the conclusions of the study.

2. Methodology

The methodology for measuring equity in transit provision consists of three stages: (i) measure of transit connectivity, (ii) calculation of location-based and potential-accessibility measures, and (iii) computation of Gini coefficients per measure and per area.

2.1. Transit connectivity

The measure of transit connectivity derives from the modification of the algorithm proposed by Ceder (2007) to accommodate multiple paths per origin–destination pair in the complex multi-modal network. The description of the algorithm follows, while the details of its mathematical formulation are provided in the Appendix.

The measure of transit connectivity requires the input of a multi-modal transit network represented by a directed graph $G(V,A)$ and a zone system. The set V of vertices contains (i) zone centroids and (ii) transit stops, while the set A of arcs contains (i) connectors from the centroids to the stops, (ii) transit line arcs between the stops, and (iii) transfer connectors between lines at the stops. Moreover, the measure requires the input of a schedule-based transit assignment that loads the demand for transit between origin zones O_i and destination zones D_j (see, e.g., Sheffi, 1985; Nielsen, 2000). The transit assignment produces level-of-service variables for each mode and each link: in-vehicle times, walking times, waiting times, scheduled headways, transfer times, and number of passengers. The calibration of the transit assignment (i.e., comparing the modeled number of passengers with vehicle counts) also produces the ratios of substitution between time components (e.g., 1 min of in-vehicle time on a bus is equal to 0.75 min of in-vehicle time on the metro and 1.14 min of walking time).

The algorithm consists of the following steps:

- Initialize the network with the level-of-service variables, consider the values e_a^q of the attributes e^q for every arc a, and normalize their scale over the A arcs to make the connectivity measures comparable.
- For each origin–destination pair, generate a set of multi-modal paths connecting origin zone O_i and destination zone D_j and calculate the values of the attributes e^q for every generated path.
- For each origin–destination pair, calculate the values e_p^q of the attributes e^q by averaging over the set of multi-modal paths, and consider the weights ω_{eq} for each attribute e^q.
- For each origin–destination pair, calculate the transit connectivity C_{ij} between origin zone O_i and destination zone D_j.

$$C_{ij} = \sum_{e^q \in E} c_p^q = \sum_{e^q \in E} (\omega_{e^q} \cdot e_p^q) \quad \forall p \in P_{ij} \tag{1}$$

The generation of the set of multi-modal paths relies on the computation of k-shortest paths minimizing the total travel time and k-shortest paths maximizing the total passenger flow. This allows expressing the connectivity as a function of the most logical paths, namely the fastest and the most frequently used ones.

The calculation of transit connectivity relies on 11 attributes e^q. The first 8 attributes are the averages and standard deviations of in-vehicle time, walking time, waiting time, and scheduled headway, and they are calculated over the set of multi-modal paths. While in-vehicle time and waiting time are self-explanatory, the waiting time represents the penalty for delaying the departure from home in presence of schedule information, while the scheduled headway expresses the preference of travelers for frequent services. The 3 remaining attributes are the minimum number of transfers and the transfer times calculated respectively within and across modes. Although all 11 attributes are quantifiable, the first 8 represent quantitative aspects of the transit system, while the remaining 3 represent qualitative aspects such as the smoothness of transfers within and across modes as possibly perceived by transit users. The weights ω_{eq} are based on the ratios of substitution from the calibration of the schedule-based traffic assignment. The transit connectivity C_{ij} for each O_i–D_j pair is measured in minutes, and a lower absolute value of this weighted time measure indicates higher connectivity.

With respect to the original algorithm proposed by Ceder (2007), two key modifications were proposed to allow the application to a large-scale multi-modal network: (i) generation of a set of multi-modal paths in order to allow for the equity assessment to account for the probabilistic nature of path choice; (ii) integration with a schedule-based traffic assignment in order to allow for the equity assessment to rely on information concerning the demand and to consider heterogeneity in the preferences for modes and paths across travelers. The Appendix details the steps of the algorithm and presents a streamlined notation that is different from the original one proposed by Ceder (2007).

2.2. Location-based and potential-accessibility measures

The calculation of the transit connectivity C_{ij} between each origin zone O_i and each destination zone D_j allows calculating location-based and potential-accessibility measures.

Location-based measures relate to the calculation of the transit connectivity at the zone level. Consider the set $P_{Oi} = \{P_i\}$ of multi-modal connections from origin O_i to all the destinations D_j, and similarly consider the set $P_{Dj} = \{P_j\}$ of multi-modal connections from all the origins O_i to destination D_j. Having computed the transit connectivity C_{ij} for each O_i–D_j pair, define the origin connectivity C_i for each zone as the origin O_i of transit trips destined in the entire area and the destination connectivity C_j for each zone as the destination D_j of transit trips originated from the entire area:

$$C_i = \sum_{p \in P_{O_i}} C_{ij} = \sum_{p \in P_{O_i}} \left(\sum_{e^q \in E} (\omega_{e^q} \cdot e_p^q) \right) \tag{2}$$

$$C_j = \sum_{p \in P_{D_j}} C_{ij} = \sum_{p \in P_{D_j}} \left(\sum_{e^q \in E} (\omega_{e^q} \cdot e_p^q) \right) \tag{3}$$

The origin connectivity C_i measures the connectivity of each zone O_i to every other zone in the study area, and hence the prospect for the population living in zone O_i to reach opportunities (e.g., jobs, universities, hospitals) in every other zone. The destination connectivity C_j measures the connectivity of each zone D_j to every other zone in the study area, and hence the prospect of the opportunities in zone D_j to be accessible by the population living in every other zone. The connectivity C_{ij} for each O_i–D_j pair expresses the possibility of the population living in zone O_i to reach the opportunities located in zone D_j.

Potential-accessibility measures relate to the calculation of the connectivity at the zone level and the size of the zone. This study defines the public transport connectivity provision $PTCP_i$ of each zone by adapting the formulation of the public transport provision suggested by Monzón et al. (2013):

$$PTCP_i = \sum_{D_j \in D} \frac{P_{gi}}{C_i} = \sum_{D_j \in D} \frac{P_{gi}}{\sum_{p \in P_{O_i}} \left(\sum_{e^q \in E} (\omega_{e^q} \cdot e_p^q) \right)} \tag{4}$$

The $PTCP_i$ weighs the origin connectivity C_i according to the size that may be expressed as a portion P_{gi} of population or opportunities (e.g., number of students, number of jobs), in order to express the facility to reach a locus of opportunity. The $PTCP_i$ increases for an increase in the population or the opportunities offered and for an increase in connectivity that corresponds to a lower absolute value of the weighted time between zones.

2.3. Equity assessment

The assessment of equity in transit provision relies on the visualization of the location-based and potential-accessibility measures in the study area and the calculation of Gini coefficients expressing the degree of inequality.

With respect to the original algorithm proposed by Ceder (2007), the presentation of the results is a third key modification. In a large-scale multi-modal network in fact, it is nearly impossible to produce tables and graphs that would include all the transit connectivity values for a large amount of zones. The location-based and potential-accessibility measures are calculated for each zone, their empirical distributions are observed for the study area, and maps are constructed in which each zone has one color on a scale from the lowest to the highest quintile. The socioeconomic characteristics of the zone are treated and mapped in similar fashion. The visual comparison of the distribution of location-based and potential-accessibility measures with the distribution of socioeconomic characteristics provides insight into the spatial (e.g., location-based measures vs. population density), vertical (e.g., location-based measures vs. income) and intergenerational equity (e.g., potential-accessiblity measures vs. specific population group) in the study area. The measure of transit connectivity is performed with Matlab for the generation of the set of multi-modal paths and ArcGIS with SQL database queries for the calculations on the network and the composition of the maps of measure distributions.

The visual assessment of equity in transit provision is supported by the calculation of Gini coefficients expressing the overall degree of inequality of transit provision. Having calculated the empirical distributions of the location-based and potential-accessibility measures and having retrieved the empirical distributions of the socioeconomic characteristics of the population, the Gini coefficient can be approximated as:

$$G_z = 1 - \sum_{k=1}^{K} (X_k - X_{k-1})(Y_k + Y_{k-1}) \quad (5)$$

where G_z is the Gini coefficient for area $_z$, X_k is the cumulated proportion of the population variable ($k = 0, ..., K$ with $X_0 = 0$, $X_K = 1$), and Y_k is the cumulated proportion of the location-based and potential-accessibility measure ($k = 0, ..., K$ with $Y_0 = 0$, $Y_K = 1$). The Gini coefficient varies between *0* and *1*, with 0 indicating perfect equality and 1 perfect inequality.

3. Case study

This section introduces the study area and the rationale for the selection of the equity levels to be assessed in the GCA.

3.1. Study area

This study focuses on the GCA, which comprises 18 municipalities extending for about 3000 sq.km. with a population of about 2 million people. The planning and the development of the transit system in the GCA follows the finger-plan directives (see Knowls, 2012), which indicate five cities (Køge, Roskilde, Frederikssund, Hillerød and Helsingør) as the direction from Copenhagen for the fingers to be served by transit and road connections.

The transit network of the GCA consists of seven major modes: (i) metro, (ii) local trains, (iii), suburban trains (S-trains), (iv) regional and intercity trains (Reg-trains and IC-trains), (v) regular buses, (vi) high-frequency buses (A-buses), and (vii) suburban and express buses (S-buses and E-buses). The metro serves central Copenhagen and the airport. The Reg- and IC-trains lead north and west of Copenhagen, while the S-trains follow the radial finger lines from central Copenhagen to the mentioned five cities. E-buses and S-buses serve the S-train stations (primarily in rings), A-buses operate in central Copenhagen, and the remaining buses run in Copenhagen, the suburbs and the rural areas at a lower frequency. Fig. 1 provides an overview of the transit network in the GCA with the representation of train lines and metro lines over the dense background of the bus lines.

The GIS representation of the transit network consists of 264 traffic zones from the LTM, 2400 connectors, 222 transfer arcs, 34,752 transit line arcs, 22 metro stations, 89 train stations, and 1181 bus stations. Accordingly, the network $G(V,A)$ for this study consists of 1292 vertices and 37,374 arcs, with attributes e_a^q for the morning peak-hours (7am-9am) being digitized and entered into Matlab codes for *k*-shortest path calculations and ArcGIS SQL queries for connectivity computations.

The LTM was the main source of information. Firstly, arc attributes e_a^q were retrieved from the LTM transit assignment that produced the values for in-vehicle times, waiting times, walking times, headways and passenger flows on the arcs. Secondly, weights ω_{eq} were retrieved from the calibration of the traffic assignment to represent heterogeneity in mode preference and time perception: metro and S-trains were preferred to trains and buses, and walking and waiting times were perceived more sensibly than in-vehicle times. Thirdly, demographic (e.g., population, density, age groups) and socioeconomic (e.g., income, employment) attributes were reported for the population in the 264 origin zones O_i and destination zones D_j.

3.2. Equity assessment

Given the network $G(V,A)$, arc attributes e_a^q, weights ω_{eq} and characteristics of origins O_i and destinations D_j, the proposed method was applied. With respect to the original algorithm proposed by Ceder (2007), the fourth modification is that this specific case does not consider (i) the availability of easy-to-observe and easy-to-use information channels and (ii) the interagency connectivity satisfaction. The former was assumed to be equally distributed over the GCA, as timetables are reported at every transit station, real-time electronic information is largely available throughout the metropolitan area and smartphone applications are widely used. The latter was assumed to be irrelevant, as the GCA transit system is franchised and a planning agency (MOVIA) coordinates the fare collection and the strategic and tactical planning across operators, thus fostering the smoothness of the inter-operator connectivity throughout the study area.

Equity assessment was performed for the morning peak-hour (7–9am), and hence measure computations focus on mandatory activities (i.e., work and higher-education). Specifically, the assessment focused on (i) spatial and vertical equity with respect to employment opportunities, (ii) spatial equity with respect to professional networking opportunities, (iii) inter-generational equity with respect to higher-education opportunities, and (iv) inter-generational equity with respect to knowledge-based employment opportunities.

The rationale behind these four equity assessments lies in their relevance. Firstly, equity with respect to employment opportunities is fundamental in relation to the need to increase social inclusion in the labor market, provide opportunities for higher earnings, and reduce time-poverty. Secondly, equity with respect to professional networking is essential with regard to the need to accumulate knowledge through intra- and inter-organizational social networks that serve as an important channel for tacit knowledge accumulation, a necessary tool for skill development and innovation, and an instrument for alliance formation. Thirdly, equity with respect to higher-education opportunities is important pertaining to the enlargement of the locus of opportunities for graduates and undergraduates aspiring to employment and higher wages, and the need for inclusion in academic activities, ability in using knowledge resources, and opportunity in networking as part of campus life. Last, equity with respect to knowledge-based employment opportunities is central in connection with the promotion of youth employment through internship programs that enable the acquisition of experience, the development of skills and professional networks, and the increase in familiarity with the labor market.

4. Results

This section presents the maps and the Gini coefficients for the assessment of equity in transit provision in the GCA during the morning peak-hour.

4.1. Spatial and vertical equity with respect to employment opportunities

The spatial and vertical equity with respect to employment opportunities were measured by comparing the distributions of origin and destination connectivity (location-based measures)

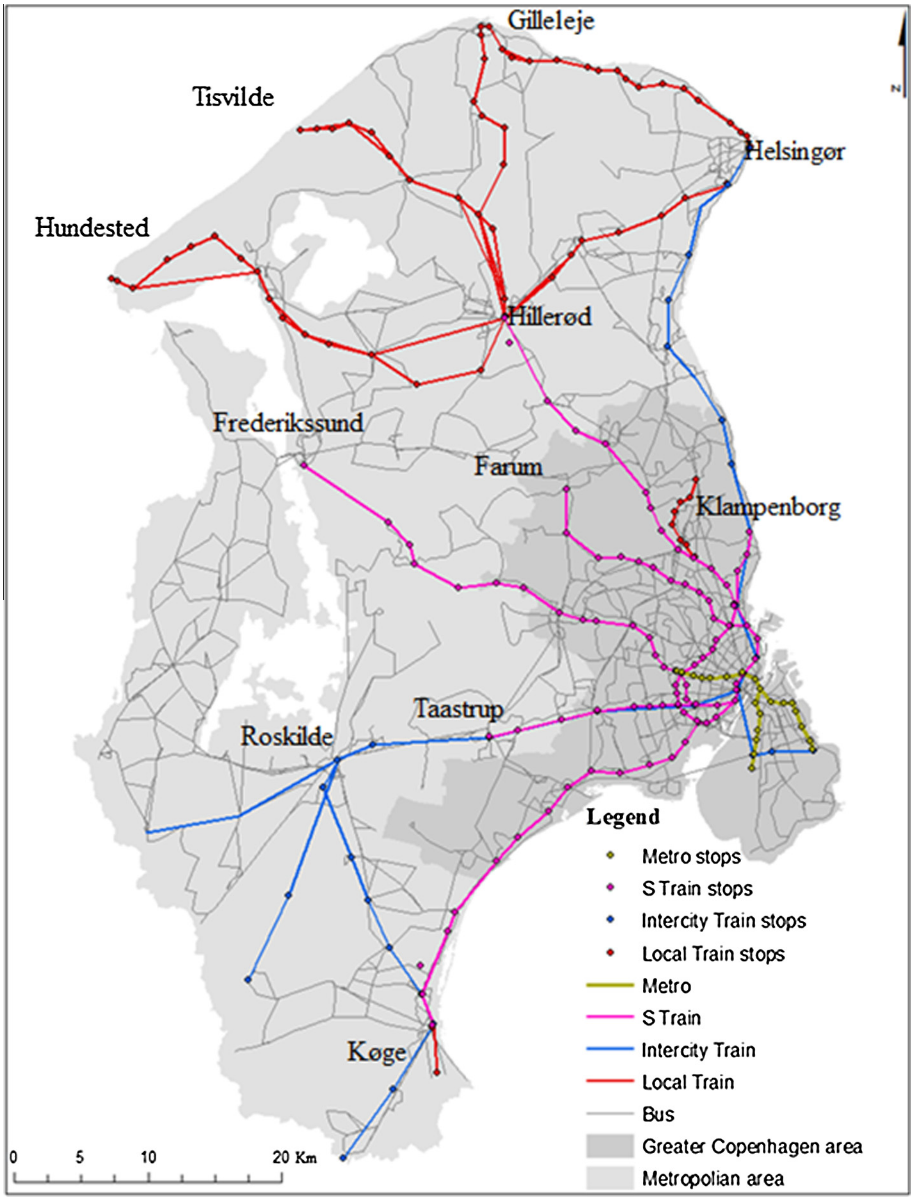


Fig. 1. Transit network of the Greater Copenhagen Area.

with the distributions of population density, average income and number of jobs (socioeconomic characteristics). Fig. 2 illustrates these distributions over the GCA traffic zones alongside a representation of origin connectivity as a graph of connectivity values alongside the corresponding map, in order to relate the proposed approach to the visualization of the results to the traditional approach proposed by Ceder (2007). The values in the graph are presented at an aggregate municipality level because of the large number of zones in the study area, while the maps are presented at the traffic zone level.

From the comparison of the distributions of the origin connectivity and the population density on the maps and the calculation of a Gini coefficient equal to 0.3254, emerges the general equality of the GCA in terms of spatial equity. The degree of equality is explained by the advantage of the transit-oriented finger-plan development, where zones with higher population density in the metropolitan core and along the train lines enjoy better connectivity. Nevertheless, the 'fingers' do not share the same level of equality within the finger-plan because the same origin connectivity is not observed throughout. More equitable areas (i.e., higher connectivity) are observed along the the south-west 'finger' to Roskilde (Gini = 0.2341) and the north 'finger' to Hillerød (Gini = 0.2953), and partially along the east 'finger' to Helsingør (Gini = 0.3743) only until the boundary of Greater Copenhagen. Less equitable areas (i.e., lower connectivity) are observed along the north-west 'finger' to Frederikssund (Gini = 0.4653) and the south 'finger' to Køge (Gini = 0.4595). The map reveals that the lower connectivity along these 'fingers' is in conflict with their high population density and is comparable to the connectivity of the low density outskirts of the metropolitan area.

From the comparison of the distributions of the origin connectivity and the average income on the maps and the calculation of a Gini coefficient equal to 0.1276, emerges good vertical equity. The zones with the highest average income enjoy better connectivity, and the zones that are less better-off in terms of connectivity are not much worse-off in terms of income. The 'fingers' exhibit comparable vertical equity with respect to income (Gini coefficients varying between 0.1207 and 0.1452), with exceptions located

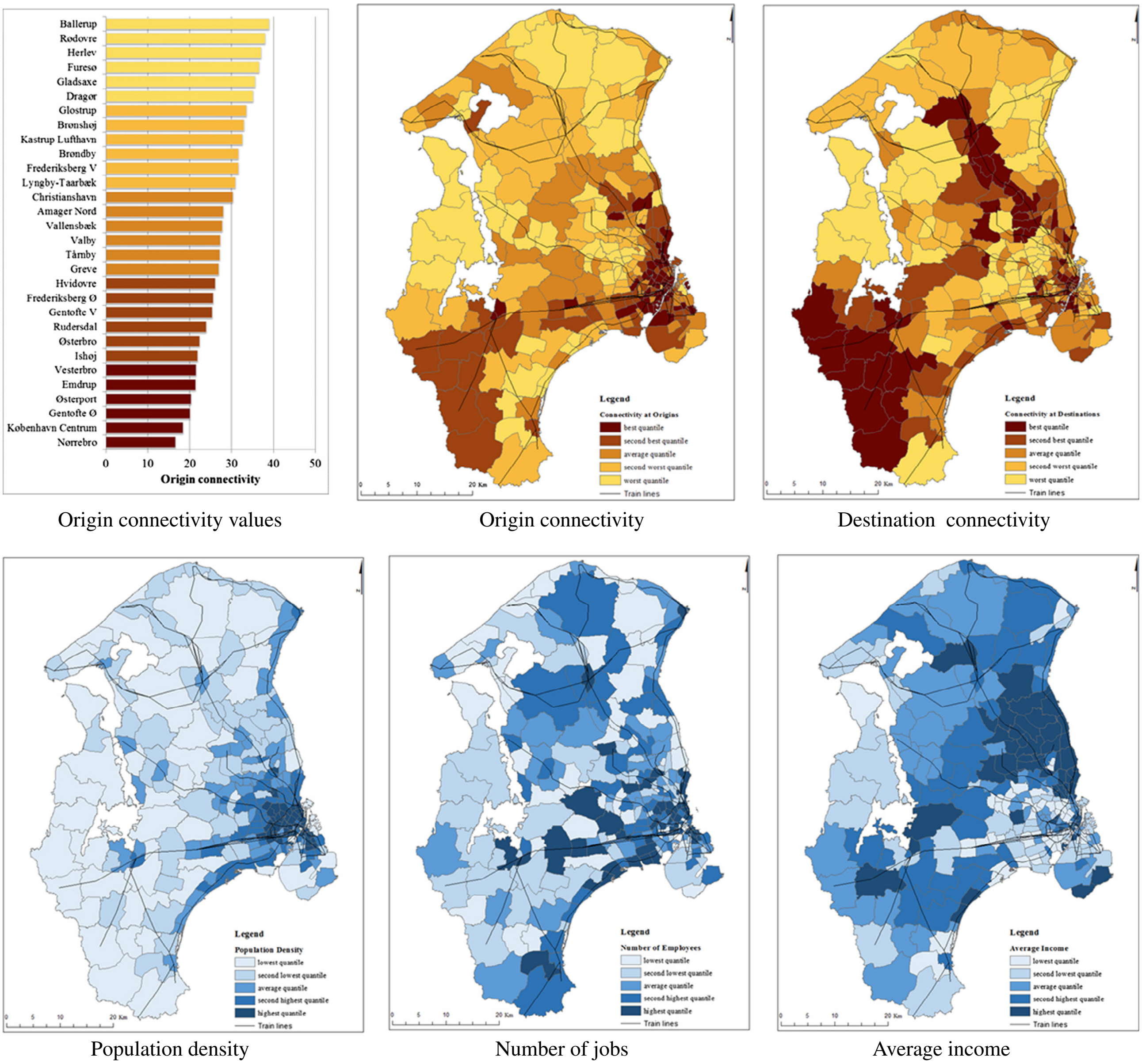


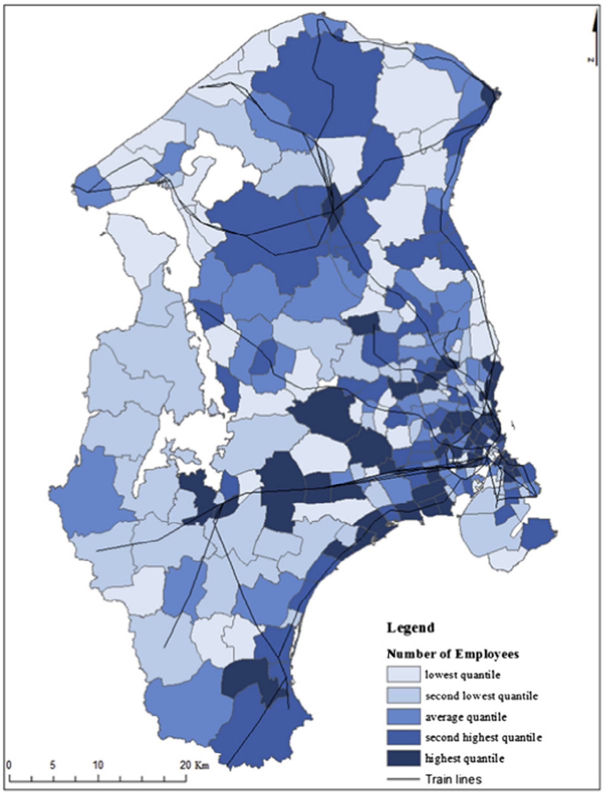
Fig. 2. Maps for the assessment of spatial and vertical equity with respect to population density and employment opportunities.

between the train lines to Farum and to Roskilde (Nørrebro, Emdrup, Gentofte Ø, Vesterbro), with high population density in the lowest income quintile suffering the worst connectivity, and east of the Roskilde fjord, with low population density with low income having low connectivity.

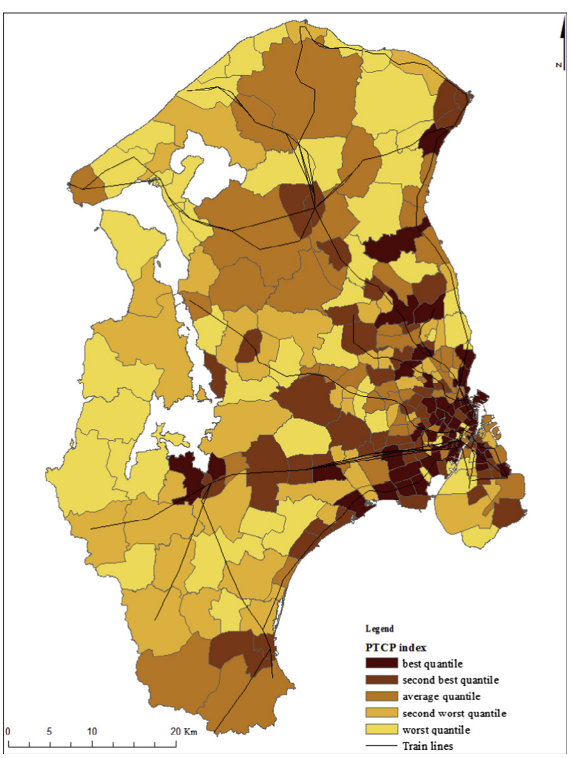
From the comparison of the distributions of the destination connectivity and the number of jobs on the maps and the calculation of a Gini coefficient equal to 0.1364, emerges equality in the GCA in terms of spatial equity with respect to employment opportunities. Although most jobs are located in the metropolitan core and along the train lines of the finger-plan, not all 'fingers' are similarly equitable. The metropolitan core enjoys the highest level of destination connectivity, and the destinations along the north 'finger' to Hillerød (Gini = 0.1148) and the south-west 'finger' to Roskilde (Gini = 0.1309) are the most equitable. Less equity related to lower connectivity are observed for the jobs located along the south 'finger' to Køge (Gini = 0.1620) and more markedly along the north-west 'finger' to Frederikssund (Gini = 0.2289). Considering the high number of jobs in this area and the low level of destination connectivity, a spatial mismatch emerges between employment opportunities and location-based measuresalong the north-west 'finger' to Frederikssund, and this mismatch is even more evident in the suburbs near the metropolitan core.

4.2. Spatial equity with respect to professional networking opportunities

The spatial equity with respect to professional networking was measured by comparing the distributions of *PTCP* (potential-accessibility measure) with the distributions of number of jobs (socioeconomic characteristic). Fig. 3 shows these distributions over the GCA traffic zones. The locus of social knowledge, namely the location of the possibility for knowledge-sharing via intra- and inter-organizational networking, was measured as *PTCP* by dividing the number of workers employed in each zone by its connectivity to all other zones as a measure of the potential of work-related meetings with employees in the other zones.



Number of jobs



PTCP to the locus of social knowledge

Fig. 3. Maps for the assessment of spatial equity with respect to professional networking opportunities.

From the comparison of the distributions of the PTCP and the number of jobs on the maps and the calculation of a Gini coefficient equal to 0.2049, spatial equity is observed in the GCA with respect to networking opportunities. This Gini coefficient relates to the figure showing the advantage of the transit-oriented development in facilitating connectivity to the locus of social knowledge in the GCA. Large concentrations of employees work in the metropolitan core and along the 'fingers', which ensures good potential networking opportunities with employees in different employment centers. Nevertheless, there are less equitable areas along the Copenhagen-Taastrup line (Gini = 0.2654) and between the Copenhagen-Taastrup line and the north-west 'finger' toFrederiskssund (Gini = 0.2893). Improving connectivity along these lines could help, considering the mismatch between the number of employees and the *PTCP*.

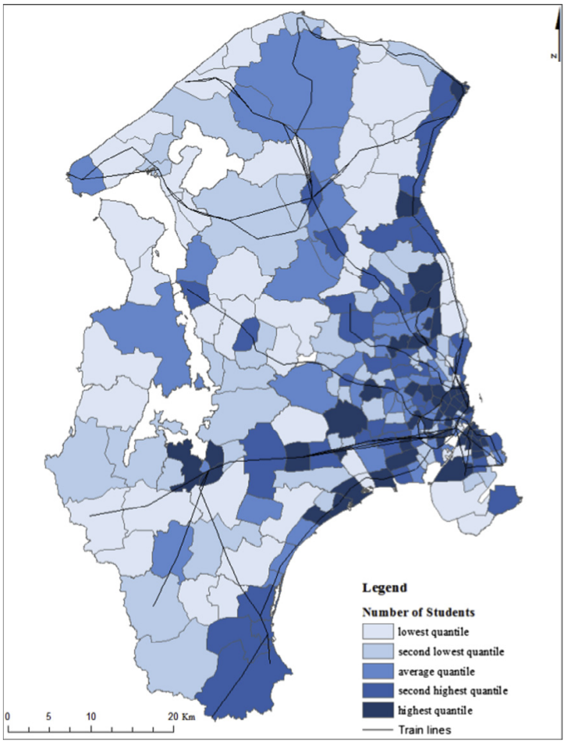
4.3. Inter-generational equity with respect to higher-education opportunities

The inter-generational equity with respect to higher-education opportunities was measured by comparing the distributions of the connectivity to the zones containing university campuses (location-based measure) with the distribution of the number of students (socioeconomic characteristic). Fig. 4 shows these distributions over the GCA traffic zones alongside the location of the university campuses. The residential location of students was extracted from LTM data about 18–25 year-old residents that are registered as students. The university locations were the campuses in the GCA of DTU, Copenhagen University, Roskilde University, Aalborg University, University of Southern Denmark, Copenhagen Business School, IT University of Copenhagen, and Copenhagen School of Fine Arts. Although some faculties are located outside the main campuses around the city, the assessment of connectivity was conducted with respect to the main campuses as the main academic and administrative service providers. The connectivity from each zone to all the universities was calculated because of university specialization and capacity constraints, and hence the locus of higher-education opportunities for students in each zone was measured.

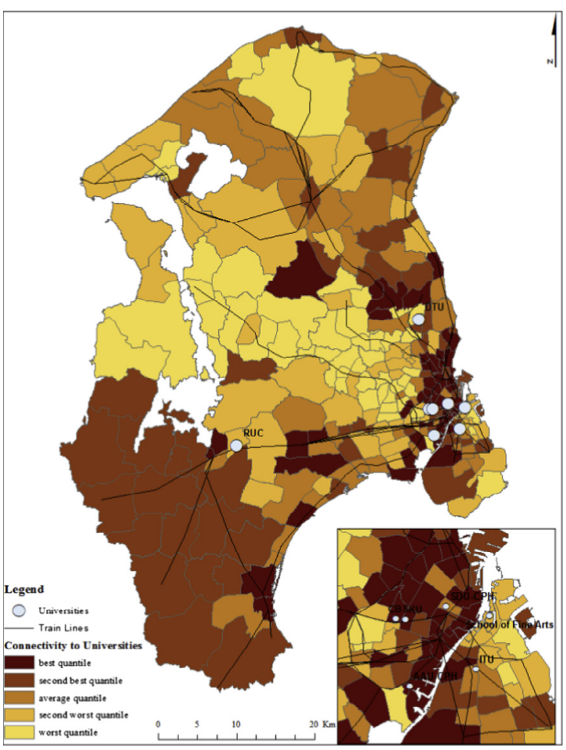
From the comparison of the distributions of the origin connectivity to universities and the number of students on the maps and the calculation of a Gini coefficient equal to 0.1961, inter-generational equity is observed in the GCA with respect to the higher-education opportunities. Naturally, the equity relates to many students concentrating in proximity to the main campuses and enjoying a high level of connectivity, but also several students living in both the southern and northern outskirts of the metropolitan area and enjoying relatively good connectivity to higher-education campuses. The less equitable area is located between the line to Farum and the line to Frederikssund (Gini = 0.2780), where a large concentration of students resides in an area characterized by relatively poor connectivity despite its spatial proximity to the city center and the main campuses. An example is Tingbierg Kollegiet, a student accommodation facility with a capacity of 300 rooms for DTU students that is located 15 km from DTU and is served by a bus-train-bus combination with a travel time of approximately 45 min. A recent survey conducted among 100 students in Tingbierg Kollegiet has revealed that 37% commute by public transport, 58% commute by bicycle, and 94% of the students had interest in establishing a shuttle bus service between the facility and the campus (Popoks et al., 2012).

4.4. Inter-generational equity with respect to employment opportunities

The inter-generational equity with respect to employment opportunities was measured by comparing the distribution of the PTCP to knowledge-based locations (potential-accessibility measure) with the distribution of the number of students

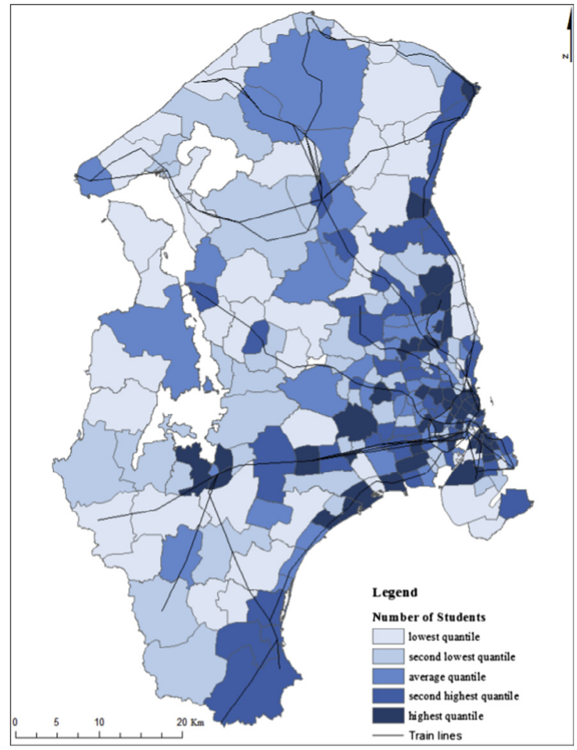


Number of students

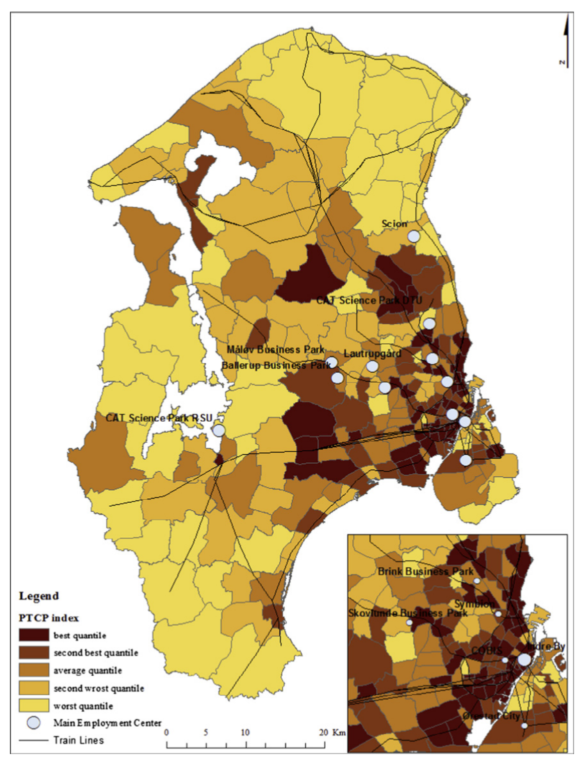


Connectivity to university main campuses

Fig. 4. Maps for the assessment of inter-generational equity with respect to higher-education opportunities.



Number of students



PTCP to CBD and knowledge-based employment

Fig. 5. Maps for the assessment of inter-generational equity with respect to employment opportunities.

(socioeconomic characteristic). Fig. 5 shows these distributions over the GCA traffic zones alongside the location of the knowledge-based locations. Specifically, the main compounds were selected to represent a wide range of knowledge-based and business industries in the GCA: CBD, Ørestad City, Symbion, Brink Business Park, COBIS and Skovlunde business park, CAT Science Park and Scion in the north, Ballerup business park, Måløv business park, and Lautrupgård in the east, and CAT Science Park RSU in the eastern outer ring of the metropolitan area. The connectivity measures the spatial locus of employment opportunities for students in each zone by calculating the connectivity from each residential zone to all the potential employment compounds.

From the comparison of the distributions of the connectivity to knowledge-based locations and the number of students on the maps and the calculation of a Gini coefficient equal to 0.2362, inter-generational equity is observed in the GCA with respect to employment opportunities. In comparison, the Gini coefficient is equal to 0.2703 when considering not a specific generation (18–25 years old), but all the employees in the area. The figure illustrates that students located near the metropolitan core and immediately north or south of the core enjoy high connectivity to the main knowledge-based locations. The value of the Gini coefficient when considering students is explained by the fact that zones with high student concentrations enjoy the best connectivity, but also zones with a low number of students have reasonably average connectivity. Thus, the transit-oriented development supports inter-generational equity by providing an adequate transport infrastructure to the Danish dual system combining higher-education and internship opportunities. The less equitable area is along the north-west 'finger' to Frederikssund (Gini = 0.3440), where a large concentration of students resides in an area of relatively poor connectivity despite its spatial proximity to the city center and many knowledge-based locations.

5. Conclusions

The calculation of transit connectivity in the morning peak-hour, the visual representation of connectivity and socioeconomic zone characteristics, and the calculation of the Gini coefficients for both the entire GCA and specific peculiar areas allowed assessing equity in transit provision. The GCA is broadly equitable from the spatial perspective, with a Gini coefficient about 0.33 with respect to population density that is sensibly lower than the 0.68 computed for Melbourne (Delbosc and Currie, 2011) and the 0.48–0.83 calculated for the Washington and Baltimore areas (Welch and Mishra, 2013). These findings show that the transit-oriented development of the finger-plan is generally beneficial from a spatial equity perspective, since densely populated areas enjoy high origin connectivity, and areas offering high numbers of jobs enjoy high destination connectivity. Nevertheless, findings concerning the 'fingers' also show that, despite similarities in the distribution of population and employment along the 'fingers', the level of spatial equity is generally worse along the north-west 'finger' to Frederiksund. Most likely, the lower frequency of the trains to Frederiksund and the longer access times to the stations on the lines along this 'finger' cause a decrease in connectivity and hence in potential-accessibility. This result demonstrates the importance of considering a comprehensive measure of transit provision rather than a simple measure of infrastructure-based accessibility, as for example proximity to transit would not grasp the complete service evaluation.

The GCA is broadly equitable also from the vertical perspective, since the zones with the highest average income enjoy better connectivity, and the zones that are less better-off in terms of connectivity are not much worse-off in terms of income. Nevertheless, the assessment of vertical equity shows that there are exceptions in zones that are highly-populated, have a low average income and have a relatively low connectivity level, albeit their proximity to the metropolitan core.

When looking at inter-generational equity, the transit-oriented development of the finger-plan is beneficial in terms of opportunities to reach the locus of knowledge as element that encourages economic and social mobility of younger generations. As most workplaces are located in the metropolitan core and along the train lines, it is equally easy for employees throughout the CGA to have opportunities for meetings with other employees across the area. The high connectivity to zones with high number of employees relaxes the need for geographical proximity and facilitates face-to-face interactions, which are still an important factor in tacit knowledge-sharing. The opportunities to reach higher-education institutions and knowledge-based locations is crucial for the student population, and findings show inter-generational equity that increases the employability of university graduates. Although generally equitable, the GCA shows a cavity in inter-generational equity in the western suburb near the metropolitan core where a large concentration of students suffers low connectivity, and this issue is important since several university dormitories are located in this area.

Overall, the study proves effective in computing location-based and potential-accessibility measures and assessing the equity of public transport provision in a large-scale multi-modal transport network. The proposed method may be readily applied to other study areas, given the increasing availability of GIS networks including information on schedules and the growing development of large-scale traffic assignment models. The availability of disaggregate data about commuting flow data, commuting flows by socioeconomic characteristics, and detailed information about job market dynamics could potentially open avenues for providing further insights into the evaluation of equity with respect to transit provision.

Appendix A

This appendix details the formulation of the algorithm for the calculation of transit connectivity for a path connecting an origin–destination pair, modified from Ceder (2007).

Consider a transit network represented by a directed graph $G(V, A)$, where V is the set of vertices v and A is the set of arcs a. Consider the following definitions:

- $O = \{O_i\}$ is the set of origins O_i;
- $D = \{D_j\}$ is the set of destinations D_j;
- $P_{ij} = \{p_{ij}\}$ is the set of multi-modal paths p_{ij} connecting origin O_i and destination D_j;
- $M_p = \{m\}$ is the set of transit modes m included in path p_{ij};
- $E = \{e^q\}$ is a set of quantitative and qualitative attributes e^q;
- ω_{eq} is the weight for each attribute e^q;
- e^q_a is the value of attribute e^q for arc a;
- e^q_p is the value of attribute e^q for path p, equal to the sum of e^q_a over the arcs composing path p;
- c^q_p is the connectivity c^q relative to attribute e^q for path p.

The calculation of transit connectivity in the transit network $G(V,A)$ for a given time window (e.g., peak-hour) follows the following algorithm:

- *Step 0.* Define the set O of origins and the set D of destinations, list the N O_i–D_j pairs, and consider the following arc attributes e^q_a:
  - in-vehicle time $tt_{a,m}$ for mode m on arc a;
  - walking time tl^{cn}_a on arc a that is a connector cn between an origin and a stop;
  - walking time tl^{ch}_a on arc a that is a transfer arc ch between stops;
  - waiting time tw_a at the initial stop v of arc a;
  - scheduled headway th_a at the initial stop v of arc a;
  - transfer time tr^{ch}_a for any mode on arc a that is a transfer arc ch between stops;
  - transfer time $tr^{ch,m}_a$ for mode m on arc a that is a transfer arc ch between stops.
- *Step 1.* For O_i–D_j pair n, create the set P_{ij} of multi-modal paths p_{ij}:
  - find k-shortest paths by minimizing path travel time (i.e., considering travel time as impedance on arc a), and add them to the set P_{ij};

– find k-shortest paths by maximizing path demand (i.e., considering average number of passengers as impedance on arc a), and add them to the set P_{ij}.

- *Step 2*. For each arc attribute e_a^q, normalize its scale over the A arcs to make the connectivity measures comparable (Ceder, 2007; Ceder et al., 2009):

$$\|e_a^q\| = \frac{e_a^q}{\sum_{a\in A} e_a^q} \quad \forall a \in A \tag{A1}$$

- *Step 3*. For O_i–D_j pair n and each path p in the set P_{ij} composed by $2k$ paths, calculate the following path attributes from the normalized arc attributes (the normalization notation and the origin–destination notation in the path are dropped to improve readability):

– in-vehicle time $tt_{p,m} = \Sigma_{a\epsilon p}(tt_{a,m})$ for mode m on path p;
– walking time tl_p^{cn} on connector cn between O_i and boarding stop of path p;
– walking time tl_p^{ch} on transfer arcs ch between stops of path p;
– walking time $tl_p = tl_p^{cn} + tl_p^{ch}$;
– waiting time tw_p at the boarding stop of path p;
– scheduled headway th_p at the boarding stop of path p;
– transfer time tr_p^{ch} for any mode on transfer arcs ch of the path p;
– transfer time $tr_p^{ch,m}$ for mode m on transfer arcs ch of the path p;
– number of transfers ch_p^v on path p.

- *Step 4*. For O_i–D_j pair n, calculate the values e_p^q of the following attributes:

– average walking time:

$$e_p^1 = \frac{1}{2k}\sum_{p\in P_{ij}} tl_p = \frac{1}{2k}\sum_{p\in P_{ij}}\left(\sum_{cn} tl_p^{cn} + \sum_{ch} tl_p^{ch}\right) \quad \forall p \in P_{ij} \tag{A2}$$

– variance of walking time:

$$e_p^2 = \frac{1}{2k}\sum_{p\in P_{ij}} (tl_p - e_p^1)^2 \quad \forall p \in P_{ij} \tag{A3}$$

– average waiting time:

$$e_p^3 = \frac{1}{2k}\sum_{p\in P_{ij}} tw_p = \frac{1}{2k}\sum_{p\in P_{ij}}\left[\frac{1}{2} th_p\left(1 + \frac{\mathrm{var}(th_p)}{th_p^2}\right)\right] \quad \forall p \in P_{ij} \tag{A4}$$

– variance of waiting time:

$$e_p^4 = \frac{1}{2k}\sum_{p\in P_{ij}} (tw_p - e_p^3)^2 \quad \forall p \in P_{ij} \tag{A5}$$

– average in-vehicle time:

$$e_p^5 = \frac{1}{2k}\sum_{p\in P_{ij}}\left(\sum_{m\in M_p} tt_{p,m}\right) \quad \forall p \in P_{ij} \tag{A6}$$

– variance of in-vehicle time:

$$e_p^6 = \frac{1}{2k}\sum_{p\in P_{ij}}\left[\left(\sum_{m\in M_p} tt_{p,m}\right) - e_p^5\right]^2 \quad \forall p \in P_{ij} \tag{A7}$$

– average scheduled headway:

$$e_p^7 = \frac{1}{2k}\sum_{p\in P_{ij}} th_p \quad \forall p \in P_{ij} \tag{A8}$$

– variance of scheduled headway:

$$e_p^8 = \frac{1}{2k}\sum_{p\in P_{ij}} (th_p - e_p^7)^2 \quad \forall p \in P_{ij} \tag{A9}$$

– number of transfers:

$$e_p^9 = \sum_v ch_p^v \quad \forall p \in P_{ij} \tag{A10}$$

– smoothness of transfer across modes:

$$e_p^{10} = \sum_{ch} tr_p^{ch} \quad \forall p \in P_{ij} \tag{A11}$$

– smoothness of transfer within modes:

$$e_p^{11} = \sum_{ch} tr_p^{ch,m} \quad \forall p \in P_{ij} \tag{A12}$$

- *Step 5*. For O_i–D_j pair n, calculate the path connectivity C_{ij}:

$$C_{ij} = \sum_{e^q\in E} (\omega_{e^q} \cdot e_p^q) \quad \forall p \in P_{ij} \tag{A13}$$

- *Step 6*. Update $n = n + 1$ and return to *step 2* for another O_i–D_j pair n, otherwise stop.

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