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CONTENTS

Photo, front cover: Magnus Rönn. The picture shows a desktop in wood. The waves in the image are annual rings.

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URBAN DENSITY AND ACCESSIBILITY: A METHODOLOGICAL APPROACH

FABIO HERNÁNDEZ-PALACIO AND TODOR KESAROVSKI

Abstract

The built environment's impact on human behaviour is well-documented. Still, quantitative research on the topic usually focuses on a large scale, with few studies at the neighbourhood level. This study presents a method investigating the correlation between the local built environment densities and accessibility. We propose a three-step approach using kindergartens in the Stavanger region, Norway, as a case. First, through GIS, we estimate the kindergartens' serviceability as a function of accessibility using 10-minute walking isochrones. Second, we statistically compare the results with density quantifications to explore the relationship between the built environment and kindergarten access. Third, through field observations, we record the travel modes used to access five kindergartens in areas representing the region's built environment diversity. The results demonstrate that populations in denser areas are more likely to walk with their children. However, the research reveals that over 12% of the region's residents live beyond a 10-minute walking distance to kindergartens, making them reliant on cars to access this service. This study aims to provide an adaptable and replicable method to evaluate accessibility to a range of crucial facilities in cities. The findings from such analyses can help optimise the built environment and the provision of services in more sustainable ways.

Keywords:
Urban density, built environment, travel behaviour, accessibility, cycling, walking, 10-minute city, GIS.

1. Introduction

There is extensive research on how the built environment affects travel behaviour in cities. This body of knowledge supports the idea that denser urban areas are less car-dependent and rely more on environmentally friendly mobility modes like public transport, cycling or walking instead of cars (Cervero & Kockelman, 1997; Rode et al., 2017). Thus, urban density is regarded as a quality to enable more sustainable lifestyles in cities (Newman, 2014). Most of the research in this field focuses on estimating travel behaviour. It tends to consider aspects within the perspective of large-scale relationships or data aggregation (on the level of towns, cities, and urban regions), an emphasis particularly evident in the Nordic countries (Næss, 2012). Examples of frequently analysed variables are distances to urban centres and sub-centres (Engebretsen et al., 2010; Næss et al., 2019), distances to specific facilities and amenities (Næss, 2011; Tennøy & Lowry, 2008), overall population and job densities (Grunfelder & Nielsen, 2012), and regional settlement structures (Næss, 2006; Tiitu et al., 2021). These factors are often studied in combination, as they are interrelated in their effect on accessibility and travel choices.

A possible explanation for the abundance of works exploring the relationships between the built environment and travel behaviour on city-wide or metropolitan scales has been the difficulty of accessing more detailed information to study the neighbourhood scale. However, advances in information and communication technologies are making more detailed quantitative studies possible. These more specific studies are especially relevant for the analysis of short-distance trips, where walking or cycling can have a larger role and where the particularities of the built environment can have a more significant impact. In recent years, there has been a growing number of works focusing on the neighbourhood-scale effects of the built environment on accessibility and travel behaviour in the Nordic context (Engebretsen et al., 2018; Mouratidis et al., 2019; Næss, 2011; Næss et al., 2017; Sundquist et al., 2017). This article aims to contribute to exploring this perspective by proposing a method to quantify the relationship between local urban densities and accessibility to frequently used urban services, kindergartens in this case.

In this study, urban density refers to the concentration of an area's buildings, infrastructures, activities, and people. Therefore, we use a set of indicators to capture the concentration of built surface, land uses, accessibility network (streets) and population (see Section 3, Table 2). For accessibility, we use the definition proposed by Miller (2018), which captures the concept's operational complexity. For Miller, accessibility refers to the varying ease or difficulty of reaching and interacting with different locations in space. It combines the factors of travel impedance, attractiveness, and the magnitude of opportunities for interaction at a specific point. Accessibility measures how close a destination is to all origins; this is the potential to interact, while actual travel represents mobility. Measuring accessibility involves integrating or summing up the opportunities in a spatial system, considering the ease of interaction.

We take the accessibility to kindergartens in the urban region of Stavanger in Norway as a case study. This city presents an intriguing case due to its low-density development, heavy reliance on cars for daily transportation, and the various policies implemented by authorities to promote walking, cycling, and public transport usage. Kindergartens are regarded as a vital and popular socio-cultural institution in Norway. They contribute to children's development and well-being and allow parents to return to the job market. According to Statistics Norway, 93.4% of children between the ages of 1 and 5 attended a kindergarten in 2021.[1] Furthermore, in Norway, the service is mainly provided by public facilities financed by the municipalities. The system allocates places to children by enabling parents to prioritise up to four choices. Two decisive factors are an already registered sibling and the distance between the assigned kindergarten and the children's home (Geitle et al., 2020). As a result, families tend to be serviced by kindergartens located in the vicinity of their homes. Therefore, they are an interesting case to explore how the diverse built environments of the neighbourhood correlate with accessibility and mobility modes to escort children to daycare institutions.

1 https://www.ssb.no/en/utdanning/barnehager/statistikk/barnehager

The analysis developed in this study seeks to answer the following question:

> *How to measure the relationship between the density of the local built environment and the accessibility to kindergartens in the Stavanger region (Norway)?*

We use the 10-minute city concept to frame this research question and explore it from three perspectives. First, through GIS data analysis, we assess the kindergartens' serviceability as a function of the capacity of each facility (the number of places for children) and its accessibility. Based on the location of each kindergarten within the urban fabric, we use network analysis to estimate 10-minute walking isochrones, referring to the accessible area around the facilities. In many neighbourhoods, two or more isochrones are overlapped, creating different serviceability scores for each area (the method is detailed in Sections 2 and 3 of the supplementary materials).[2] Based on these quantitative operations, we establish a serviceability index across the Stavanger region. Second, we correlate this metric with various density indicators and population distribution through statistical analysis. In this way, we explore the relationship between the local built environment and service opportunities for individuals as a function of accessibility. Third, we use fieldwork to observe the travel choices concerning five kindergartens in five areas representing Stavanger's diverse built environment. This way, we also register the preferred mobility modes to access the facilities in each selected case.

2 The supplementary material is published on the platform DataverseNO. It can be accessed using this link: https://doi.org/10.18710/XO6FG7

By using this approach, this study provides a scientific contribution in three main directions:

(1) It contributes to the growing scientific evidence concerning the potential of 10-/15-/20-minute city concepts by unveiling the quantitative relationship between an established urban structure and the serviceability of a specific amenity, i.e., kindergartens.

(2) It empirically explores the travel modes to perform escort trips (from and to kindergartens), characterised by 2+ travellers and correlates the observed findings with the local built environment.

(3) It proposes a mixed-method approach that combines an extensive sample correlation analysis within a GIS environment with purposeful fieldwork observations to record travel choices without relying on self-reported data. Thus, the method provides an alternative objective perspective to observe the relationship between the built environment and urban mobility.

This article is structured as follows. In the next section, we present a short literature review concerning the framework of the study. There, we discuss the importance of proximity for contemporary cities, the justification of the 10-minute walking threshold as an appropriate service isochrone for the context of Norway and the specifics of escort trips as a type of travelling. Section 3 describes the exploration and case selection methods for collecting and processing the research data. Subsequently, in Section 4, the generated results concerning the serviceability estimations, statistical correlations and field observations are presented. Section 5 discusses the derived findings within the research framework of interest and relates the outcomes to the existing scientific literature. In Section 6, we summarise the generated study results, reflect on the introduced research method's potential and limitations, and elaborate on further directions for its development.

2. Framework and context of the study

2.1 Urban density, proximity, and accessibility

Urban density is a multidimensional concept entangled with other aspects of urban form, such as land use, spatial layout, building types, and transport infrastructure (Dempsey et al., 2010). Density and urban form, in general, have been long recognised as intrinsically linked to urban performance. For example, a service or facility's viability requires a number of users. The closer the user's location, the easier the accessibility. In this regard, the concentration of users attracts the location of services and facilities that can easily access a potential clientele. In turn, the concentration of opportunities attracts more users who want more accessible opportunities. This virtuous circle explains the economic logic of cities used in numerous studies to explain the performance of different urban patterns and the importance of compact urban forms to facilitate accessibility (see, for example, Duranton, 1999; Cervero, 2001; Banister, 2008; Rode et al., 2017).

The relationship between urban density, proximity, and accessibility has been central to city planning. Already in the 19th century, as part of his famous plan for Barcelona's urban expansion, Ildefons Cerdà emphasised in his proposal a system of distributing public and commercial services based on the residential densities of individual blocks (Pallares-Barbera et al., 2011). This relationship is further explored in the work of Jane Jacobs (1961) while analysing how cities function on a *fine-grained* scale. She underlines the apparent connection between population and or dwelling densities and the generation of urban provisions, expressed, among other properties, in the diversity and quantity of provided services, i.e., the degree of serviceability.

Technological advances to capture, store, process and visualise information have broadened the possibilities of combining techniques to study the built environment. Since the 1980s, space syntax theory has provided solid explanatory models of how urban grids formed by the networks of open spaces and streets are fundamental in generating movement in cities. By favouring accessibility, denser street networks make better-connected spaces more attractive, contributing to increased built density and land use diversity. Therefore, street network configuration, building density, and land use diversity are highly interrelated aspects of urban form. (Hillier et al., 1993; Ye & Van Nes, 2013).

The development of geographic information systems (GIS) has expanded the enquiry of accessibility from multiple angles and through various concepts and techniques. Some examples are the use of network analysis to understand centrality, expressed as the potential for accessibility, in diverse urban patterns (Porta et al., 2006); the study of retail patterns in cities (Araldi & Fusco, 2019); the study of accessibility in transit-oriented development (Papa et al., 2013; Rahman et al., 2022; Schlossberg & Brown, 2004); the relationship between residential densities and serviceability (Calafiore et al., 2021; Hosford et al., 2022; Kesarovski & Hernández-Palacio, 2022; Shi et al., 2020; Um et al., 2009). All these works emphasise the significance of urban density and proximity to facilitate accessibility in contemporary cities and their implication in urban performance.

Accessibility by proximity in cities has also gained importance because of environmental and social reasons. The compact city debate has raged for three decades since the 1990s, primarily due to the evidence that denser built environments are more energy and space-efficient and enhance the possibility of face-to-face social interaction. With the urgency to achieve a carbon-neutral society to avoid catastrophic climate change, the living-local movement is experiencing a revival. Among city planners, it has led to the revival of ideas such as the 15-minute neighbourhood units proposed by Clarence Perry in the 1920s and 1930s (Kostritsky, 1951). The idea of the walkable neighbourhood, especially for children's access to schools by walking proposed by Perry, has been retaken in city planning in many contexts in concepts such as 5, 10, 15, 20 or 30-minute city as an idea to improve accessibility to services by environmentally friendly mobility modes (Capasso Da Silva et al., 2020; Levinson, 2020; McNeil, 2011; Øksenholt et al., 2016).

For this study, it seems essential to pay more attention to the work of Øksenholt et al. (2016). They explore the question of adequate proximities to avoid car dependencies in the Norwegian context through comparative simulations of different time isochrones. The authors conclude that 10 minutes of travelling should be accepted as a maximum threshold for accessing urban services if Norwegian settlements aim to facilitate a high share of active mobility modes, such as walking. This claim is further supported by the most recent Norwegian national travel survey from 2014. It reveals that most people (68%) walk for trips shorter than 1 km (approx. 12 minutes), while the percentage drops significantly when this threshold is exceeded (Hjorthol et al., 2014). Therefore, we accept 10 minutes of walking as an appropriate range for exploring the issue of proximity to kindergartens and their pedestrian serviceability in the Stavanger Region.

2.2 Challenges of estimating accessibility to kindergartens

In recent years there has been a growing interest in exploring the issue of spatial accessibility to daycare facilities and kindergartens as vital urban services (Chen et al., 2021; Fransen et al., 2015; Kim & Wang, 2019). These studies have led to methodological progress in service accessibility research based on advanced computational techniques. However, all the mentioned authors above recognise the challenges of developing an accurate metric to evaluate the physical access to such facilities. This is caused by the fact that children are escorted to kindergartens. Thus, these journeys tend to merge into other trips of the escorting adults, becoming a stop, for example, on the trip to work or the supermarket (Fransen et al., 2015). To reflect on this issue, Chen et al. (2021) developed a metric incorporating two types of trips in their model, i.e. "Home-School" and "Home-School-Work". However, this also requires a certain degree of arbitrary simplification that might not reflect the actual travel behaviour in reality, an issue recognised by the authors:

> *The present study evaluates accessibility by assigning two different weights to two types of school trips (i.e. 63.0% and 37.0%). In reality, not all parents need to commute, and 37.0% could overestimate the real proportion of trips belonging to the "Home–School–Work" category. Also, these two weights should not be uniform and could vary across different neighborhoods* (Chen et al., 2021, p. 1394).

Escort trips represent 10% of all journeys in Norway. According to the 2014 national travel survey, a significant share of these trips (41%) is escorting children from and to kindergarten, daycare, or school (Hjorthol et al., 2014). In larger Norwegian cities, such as Stavanger, 78% of these journeys are performed by car, 71% as a driver and 7% as a passenger. In contrast, 15% of these trips are executed walking, while only 4% are performed by bike and 3% by public transport. This reveals a significant car dependency. These figures motivate the present research to enquiry if the local built environment and the distribution of kindergartens are determinants of the pronounced car dependency and the low shares of walking to access daycare facilities.

While researching pedestrian accessibility, we also need to recognise the issue of average walking speeds. As Hillnhütter (2016) outlined, assigning an average walking speed requires an empirical simplification, even if analyses are performed with sufficient precision regarding the existing walking network, including waiting times at traffic lights (further details in Section 3). Defining an average walking speed seems even more complicated if we focus on escort trips involving children, as in this study. Indeed, the speed can be very different for escorting a toddler in a carrier or a five-year-old child walking and playing along the way. The absence of relevant literature on the topic confirms further the difficulty of dealing with this issue. Therefore, we use the 10-minute isochrones around each facility as a threshold to frame the research exploration. Considering these specifics, we employ the average walking speed for a healthy adult of 4.86 km/h, as defined by Montufar et al. (2007), to process the GIS-based analyses, i.e. estimating the service area polygons and aggregated serviceability scores.

3. Methodology

The revived interest in the chrono-urbanism perspective as a consolidating approach toward sustainable transformations has logically led to a growing number of empirical explorations within the framework of 10-, 15- and 20-minute cities. The applied methodology in this article aims at building upon the works of Calafiore et al. (2021), Hosford et al. (2022) and Kesarovski & Hernández-Palacio (2022). These studies focus on quantifying a degree of serviceability regarding specific amenities and identifying spatial inequalities by incorporating built environment, demographic, or socio-economic attributes. The following research is executed through a mixed-method approach, including (1) data processing and analyses within a GIS environment, (2) statistical correlations through simple linear regressions, and (3) field observations of travel choices. The following section reveals the main elements, steps, and specifics regarding the utilised research techniques.

3.1 GIS-based research

A substantial part of the executed research activities is realised within a GIS environment. These operations can be categorised into three steps. First, we integrate the data input from several sources to set the basis for quantitative modelling. Second, using GIS network analysis, we generate the service area polygons around each kindergarten. Third, we calculate the kindergarten serviceability metric for the whole region through GIS overlay analysis. Further details concerning these operations are presented in the paragraphs below and the article's supplementary materials.

3.1.1 Utilised datasets and data integration

The study integrates datasets from various sources, whose description is presented in *Table 1*. Although most are collected in geo-referred format, further adjustments are required to enable the integration. The two most significant data processing operations, part of the preparatory step, are:

- Integration of FKB-Bygning (a constructions dataset) and cadastral data to set the basis for calculating built density indicators.
- Modifying the transport networks (Elveg 2.0 dataset) to model pedestrian accessibility.

We present additional details of these two steps in Section 1 of the article's supplementary materials, where details of the original datasets and inconsistencies identified in the process are also included.

3.1.2 Generating service areas – GIS Network Analysis

The operation estimates service areas around the facilities of interest (Stavanger region's kindergartens) considering the time isochrone of 10 minutes walking. This is realised through the *GIS Network Analysis* toolset. *Section 2* of the supplementary materials presents the technical procedures' full description. Still, we want to remark on two significant details regarding the performance of this operation. First, we estimate the service areas for each kindergarten using the velocity of 4.86 km/h, identified by Montufar et al. (2007) as an average walking speed for healthy adults. Second, we incorporate time barriers (waiting times) at traffic light signals with pedestrian crossings to accurately estimate the model's service areas (39 locations in the Stavanger region). This results in the generation of an individual service area polygon around each kindergarten, bounded by the 10-minute time isochrone.

3.1.3 Estimating level of serviceability – GIS Overlay Analysis

After calculating the accessible areas, we estimate the level of serviceability within the Stavanger region by incorporating the individual capacities of the kindergartens. This activity is realised through a *GIS Overlay Analysis*. *Section 3* of the article's supplementary materials in-

Table 1
Employed datasets in the research.

DATASET	DESCRIPTION	FORMAT	SOURCE	YEAR
Census data (grunnkrets, rutenett)	Population data on different scales. The research uses two aggregation formats: 1) on the *grunnkrets* level, representing the smaller statistical units in Norway and 2) on a geographical grid of 250x250 metres cells (*rutenett*).	Geo-referred data – .shp (FGDB 10.0, SOSI 4.5)	*Statistisk sentralbyrå* – SSB (Statistics Norway)	2020
FKB-Bygning	Detailed building information, including descriptions of all types of buildings, roof superstructures, descriptive building lines (e.g., ridgeline), and building attachments (e.g., verandas)	Geo-referred data – .shp (FGDB, SOSI)	*Statens kartverk* (Norwegian Mapping and Cadastre Authority) via *Geovekst*	2020
Cadastral data	Additional information per individual building, including gross floor area (GFA), gross floor area used for housing (ResGFA), gross floor area used for other purposes than housing (OthGFA), number of units (residential - dwellings or commercial), and height (H), expressed in number of floors.	.xlsx	*Statens kartverk* (Norwegian Mapping and Cadastral Authority)	June 2020
Elveg 2.0	Road network dataset comprising all driveable roads that are longer than 50 meters or part of a network and pedestrian and cycle paths and cycle paths represented as road link geometry. The dataset is exported from the National Road Data Bank (NVDB).	Geo-referred data – .shp (SOSI)	Statens kartverk (Norwegian Mapping and Cadastre Authority) Statens Vegvesen (Norwegian Public Roads Administration)	Feb 2021
Signalegg Rogaland	A data record of the traffic light signals in the administrative county of Rogaland, including their geographical location and type.	Geo-referred data - .kml format	Rogaland fylkeskommune (Rogaland County)	Feb 2022
Barnehager	A publicly accessible dataset that records all kindergartens in Norway, including their location and individual capacities.	Geo-referred data - .shp (SOSI)	Utdanningsdirektoratet (Norwegian Directorate for Education and Training)	Aug 2021

cludes a complete description of this step. It is essential to notice that each service polygon is assigned the number of children the respective kindergarten can accommodate. Thus, the analysis does not solely determine the number of overlapping polygons but aggregates the kindergarten's capacity assigned to each polygon. Based on this metric, we can estimate the degree of kindergartens' serviceability for each area within the Stavanger region, considering the 10-minute walking isochrone. To analyse these estimations further, we aggregate the processed data to the *rutenett* dataset, representing a 250x250 metres geographical cell grid. By doing so, we evaluate the kindergartens' serviceability on a fine scale while allowing us to refer the metric to the population distribution in the Stavanger region and other urban characteristics, such as density indicators.

3.2 Linear regressions

The second part of the research operations comprises processing a series of linear regressions. This activity aims to explore statistically the extent to which the serviceability levels of kindergartens in the Stavanger region can be associated with the density indicators (see *Table 2*). This analytical step is executed by performing nine single linear regressions where the dependent variable, e.g., the estimated serviceability metric, correlates with nine density indicators as independent variables. The individual independent variables are summarised in *Table 2* and presented in greater detail in *Section 4* of the supplementary materials. The selection includes the most used density measures regarding the form of the built environment (FAR, ND, GSI and OSR), the distribution of land uses (FARre / FARoth, DWd), and the concentration of people (POPd, KIDd).

3.3 First-hand observations

The last building block of the analysis is based on first-hand observations of five selected kindergartens in the Stavanger region. These observations are conducted as a fieldwork activity to register escort trip modes in five specific facilities located within different built environments representative of the spatial diversity of the region.

3.3.1 Selection of kindergartens to be observed

Due to limitations in developing fieldwork in all kindergartens, it was necessary to select a representative sample. The resources available for this study limited us to a small number of institutions, five in total. This number was to represent the diversity of built environments in the region. Hence, we used the spatial concentration of buildings near all 241 kindergartens as the primary selection criterion to achieve this representativeness. More precisely, we employ the gross space index (GSI) indicator within the range of 800 meters from each facility along the pedestrian network (10 minutes of walking with a speed of 4.86 km/h without time barriers). The ratio between the gross building footprint and the base land area of aggregation defines GSI.

Table 2
Urban density indicators.

INDICATOR	DESCRIPTION
Floor Area Ratio (FAR)	FAR is the ratio between the gross floor area and the base land area of aggregation.
Floor Area Ratio by use (FARre / FARoth)	FAR by use is the ratio between the gross floor area for a specific function and the base land area of aggregation, in this case, residential (re) and other uses (oth).
Network Density (ND)	ND depends on networks' concentration (metric length) within a specific land area (m^2).
Gross Space Index (GSI)	GSI is the ratio between the gross building footprint and the base land area of aggregation. This is also called the Built Coverage Ratio.
Open Space Ratio (OSR)	OSR represents the percentage of open space as a proposition to the total gross floor area within a specific aggregation area.
Dwelling Density (DWd)	DWd is calculated via dwellings per hectare within a specific area; in this case, it is expressed in the "gross density" value since it refers to the gross land area.
Population Density (POPd)	POPd is calculated by the number of residents per unit area; in this case, it is calculated in people per hectare and in "gross densities".
Kids (0-4) Density (KIDd)	KIDd refers to the number of kids per unit area - in this case, the indicator is calculated similarly to POPd (per hectare and in "gross densities". However, it considers only the residents between ages 0 and 4.

To develop a GSI-based sample selection, we used a quantile classification method to distribute the GSI values of the 800-metre areas around all 241 kindergartens in five classes. This classification approach ensures linearly distributed data, where each class contains an equal number of features, i.e., 48/49. *Table 3* describes GSI thresholds, defining these five classes and outlining the GSI value of the 800-metre area around each of the selected kindergartens. It is worth mentioning that we also distinguish the percentage of housing in the kindergartens' vicinity in the selection process. As illustrated in *Table 3*, this represents the principal function of the built-up area for the respective territories in four of the selected cases. However, we have also included one deviant case concerning this parameter, i.e. *Forus privat barnehage*, to observe the travel choices to a kindergarten where housing in its vicinity is almost non-existent and where large office buildings, shopping malls, light industry, parking surface and large roads dominate the built environment.

The selection criteria also group the kindergartens into two categories. The first class are facilities in peripheral residential neighbourhoods, such as *Lærningsverkst. barnehage Jåsund* and *Kreative barnehage Bogafjell*, with 82.46% and 87.26% of housing near the facility, respectively, 10.7 and 21.1 km from the Stavanger's urban core. The second category is kindergartens in mixed-use neighbourhoods close to the centre, such as *Kampen barnehage* and *Lærningsverkst. Barnehage Lervig Brygge*, within mix-used settings, i.e. 77.07% and 66.16% of housing in the area around and distant from the centre, 1.7 and 2.2 km, respectively.

Table 3
Selected kindergartens, GSI and housing percentage within their vicinities.

CLASSES	GSI RANGES	SELECTED KINDERGARTEN	GSI	% HOUSING
Class I [49]	0.006 – 0.092	Læringsverkst. barnehage Jåsund	0.063	82.46
Class II [48]	0.092 – 0.123	Kreativ barnehage Bogafjell	0.111	87.26
Class III [48]	0.124 – 0.154	Forus privat barnehage	0.146	0.90
Class IV [48]	0.155 – 0.182	Kampen barnehage	0.175	77.07
Class V [48]	0.183 – 0.293	Læringsverkst. barnehage Lervig Brygge	0.213	66.16

3.3.2 Data collection

The observations of the selected kindergartens were executed considering seasonal differences to reflect upon the potential impact on travel choices. Thus, each of the selected facilities was examined once in the summer 2021 and winter 2022. Considering that the fieldwork was performed during the COVID-19 pandemic is important. However, there were no restrictions on kindergartens in Stavanger during the observation period; therefore, attendance remained normal. Nonetheless, work-from-home was broadly implemented, which may have increased the number of trips by foot escorting children, which, in normal driving-to-work circumstances, may have been a stop for the escorting adult. The data was collected by documenting the arrival and departure of the accompanied kids outside the entrance of each kindergarten during two timeslots on the observation days. The timeslots refer to the usual dropping off (7:00 to 9:30) and picking up (15:00 to 17:30) times for children to and from the facilities. *Table 4* documents the observation dates for each kindergarten and the dominant weather conditions for the records.[3]

3 Research data must follow the legal and ethical standards of each country. Such standards can have special considerations in research involving children and may require ethical approval from universities or national research bodies. Therefore, researchers should carefully consider the issues raised by observing children in public settings. In Norway, the *Norsk Senter for Forskingdata* is the institution monitoring the ethical standards for research data. All research using data which includes personal information (names, addresses, videos, pictures, voice records, or any other personal information) must have approval from the institution, following strict guidelines. The present research has neither registered nor used any personal information of the observed groups. Since no personal data was involved, the researcher sought approval from the directors of the involved kindergartens to develop the observations.

Table 4
Dates and weather conditions of the fieldwork observation.

SELECTED KINDERGARTEN	OBSERVATION DATE I summer 2021	WEATHER morning [mor] afternoon [aft]	OBSERVATION DATE II winter 2022	WEATHER morning [mor] evening [eve]
Læringsverkst. barnehage Jåsund	21.08.2021	Clouds [mor] Clouds [aft]	07.02.2022	Rain [mor] Clouds [eve]
Kreativ barnehage Bogafjell	22.06.2021	Sun [mor] Sun [aft]	10.02.2022	Clouds [mor] Clouds [eve]
Forus privat barnehage	21.06.2021	Clouds [mor] Sun [aft]	08.02.2022	Clouds [mor] Clouds [eve]
Kampen barnehage	19.08.2021	Sun [mor] Sun [aft]	09.02.2022	Clouds [mor] Clouds [eve]
Læringsverkst. barnehage Lervig Brygge	23.08.2021	Sun [mor] Clouds [aft]	11.02.2022	Snow [mor] Clouds [eve]

4. Findings

This section presents the research results in two parts related to the executed process. First, we focus on the results of the GIS-based analysis and the performed linear regressions. The results depict the kindergartens' serviceability in the Stavanger region and how this metric correlates with the region's spatial structure. Second, we present the findings of the fieldwork observations on the travel modes to access kindergartens. The study also links these findings with the local neighbourhood densities and pedestrian network characteristics within each kindergarten's 10-minute walking service isochrones.

4.1 Serviceability of kindergartens in the Stavanger region

First, we explore the topic of interest through quantitative geographic analyses, methodologically described in *Section 3.1*. This process allows us to estimate the serviceability index (i.e., the aggregated supply capacities of kindergartens in the Stavanger region) on 250x250 metres grid cells. The operation considers the location of each kindergarten, its capacity, i.e., the number of children who can be accommodated, and the overlapping of the computed 10-minute walking service isochrones. *Figure 1* illustrates the location and capacity of the 241 kindergartens in the region, while *Figure 2* represents the outcome of the executed computations. To structure the analysis' visual representation, we define two categorisations referring to the kindergartens' individual and aggregated supply capacities. With respect to the capacities of individual facilities (*Figure 1*), we use 0 if no children are registered, 1-25, 26-50, 51-100, and more than 100 enrolled kids. For the aggregated supply capacities across the Stavanger region (*Figure 2*), we use the thresholds of 50, 100, 150, 250 and more than 250 to define five appropriate categories of kindergartens' serviceability levels based on the available provisions and 10-minute walking service isochrones.

To go beyond the visual representations of the results, we investigate the spatial extent of the aggregated service coverage and its correlation with the built-up area (BUA) and census information. Table 5 depicts the results from these computations. Regarding spatial coverage bounded by 10 minutes of walking, we can identify that 9.88% (12 876.1 ha) of the total size of the Stavanger region is serviced. Nevertheless, considering the significant sparsely populated rural land, the analysis reveals a diverse picture of the total built-up area. Indeed, the study shows that 77.13% (2 104.36 ha) of the BUA in the Stavanger region is serviced by at least one kindergarten within a 10-minute walk. The BUA is approximately balance-distributed concerning the different serviceability index categories, containing 10 to 20% of the total BUA. Most BUA is serviced by *class 2: 51-100* (529.88 ha or 19.42% of total BUA), followed by class *4: 151-250* (473.26 ha or 17.35% of total BUA), *class 1: 1-50* (445.13 ha or 16.31% of total BUA), *class 3: 101-150* (367.16 ha or 13.46% of total BUA) and *class 5: 251+* (288.93 ha or 10.59% of total BUA).

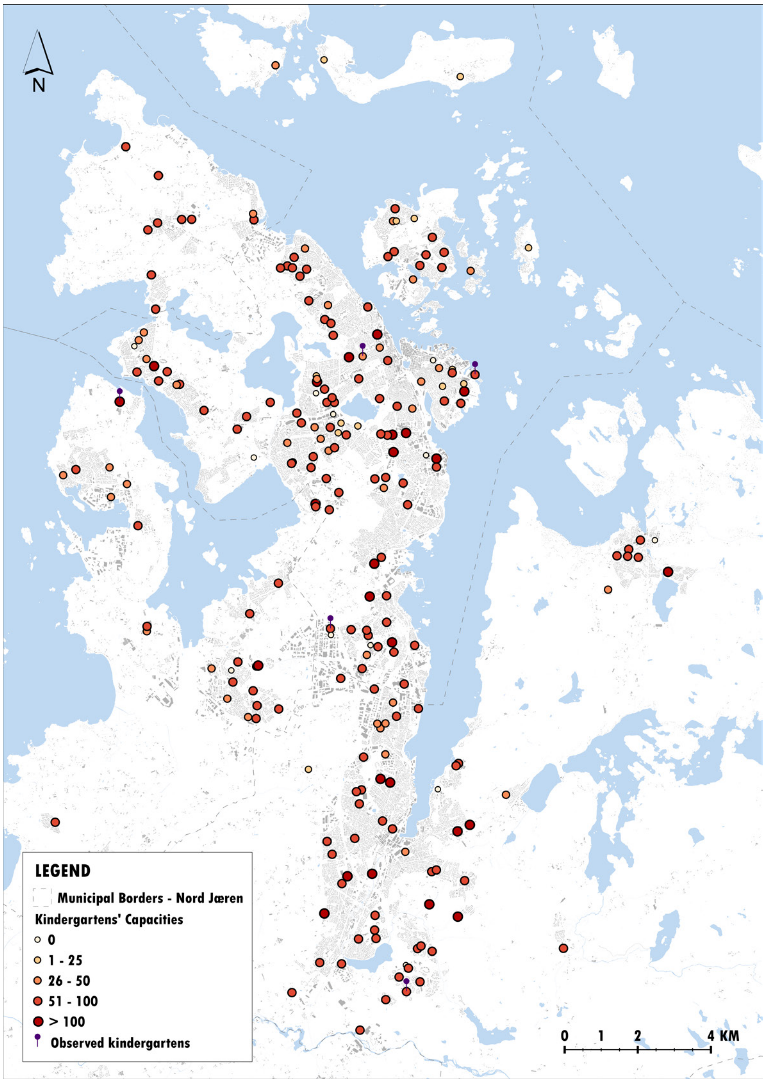

Figure 1
Location and capacities of individual kindergartens in the Stavanger region.

Slight differing result patterns can be identified by looking at the population serviced, regardless of whether we focus on all residents or only on children (aged four years or younger). We can document an even higher percentage of coverage if we focus on the demographic distribution of the Stavanger region. In particular, 228,356 (87.47%) of the total population and 14,547 (88.69%) of all kids have physical access to a kindergarten within a 10-minute walk. For both parameters, *class 4, with a serviceability index score of 151-250, represents* the largest share of the serviced population, just above 21% of the total, followed by class 2 (51-100), with a respective share of 19.64 and 19.74%. On the other hand, class 5 (*with an index score of 251+*) serves the smallest portion of both residents (13.84% or 36 145 people) and kids (14.39% or a total number of 2,360). It is worth outlining that according to the analysis, 32,664 residents and 1,855 kids cannot physically reach a kindergarten on foot within 10 minutes. These numbers represent more than 12% of all residents and 11% of all kids in the Stavanger region.

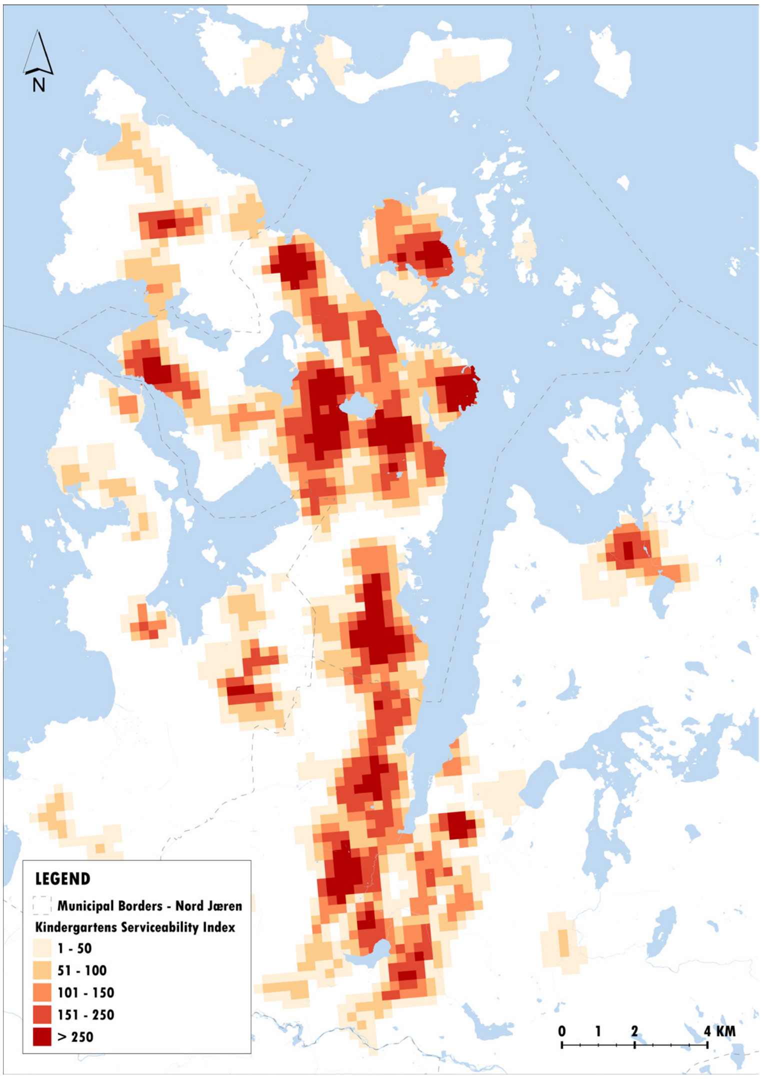

Figure 2
Aggregated kindergartens' serviceability index in the Stavanger region within 10-minute walking

Table 5
Spatial coverage, serviced population, and kindergarten capacity thresholds.

Kindergartens' serviceability index *Aggregated supply capacities	spatial coverage				population			
	Areal coverage		Built-up area coverage		Residents serviced		Kids (age 0-4) serviced	
	ha	%	ha	%	#	%	#	%
TOTAL	12 876.1	9.88%	2 104.36	77.13%	228 356	87.47%	14 547	88.69%
Class I: 1-50	5,449.4	4.18%	445.13	16.31%	40,074	15.35%	2 520	15.36%
Class II: 51-100	2,878.9	2.21%	529.88	19.42%	51,276	19.64%	3 237	19.74%
Class III: 101-150	1,657.1	1.27%	367.16	13.46%	45,370	17.38%	2 894	17.64%
Class IV: 151-250	1,833.0	1.41%	473.26	17.35%	55,491	21.26%	3 536	21.56%
Class V: 251+	1,057.7	0.81%	288.93	10.59%	36,145	13.84%	2 360	14.39%

4.2 Linear regressions of serviceability levels with density indicators

The subsequent analysis step is a series of linear regressions between the kindergarten serviceability index and various density indicators. The operation aims to build upon the estimated kindergarten serviceability within the ArcGIS environment and utilise the metric as a dependent variable in the linear regression model. On the other hand, nine density indicators (incorporating different spatial, demographic, and functional characteristics) are used as independent variables of interest (*see Table 2*). We present the statistical correlations between these variables through Pearson's correlation coefficient (R), the coefficient of determination (R^2) and the probability value of statistical significance (*p-value*). *R* refers to each relationship's positive or negative direction, R^2 indicates the model's strength, and the *p-value* represents the probability that the observed relationship might have occurred by random chance. The full details regarding this statistical operation and the considered variables are described in *Section 3.2* of this article and *Section 4* of the supplementary materials; *Table 6* presents the results of the drawn correlations.

Table 6
Linear regressions of serviceability levels with density indicators within 10-minute walking.

Density indicators	Pearson's correlation coefficient (R)	coefficient of determination (R^2)	level of statistical significance (p-value)
Floor Area Ratio (FAR)	.53	.281	< .001
Floor Area Ratio for Residential Use (FARre)	.60	.360	< .001
Floor Area Ratio for Other Uses (FARoth)	.27	.073	< .001
Network Density (ND)	.62	.384	< .001
Density of Network Intersections	.61	.372	< .001
Gross Space Index (GSI)	.61	.372	< .001
Open Space Ratio (OSR)	-.61	.372	< .001
Dwelling Density (DWd)	.58	.336	< .001
Population Density (POPd)	.63	.397	< .001
Kids (0-4) Density (KIDd)	.63	.397	< .001

The performed linear regressions underline the following statements:

- All the examined correlations have positive relationships between the dependent and independent variables, meaning that the higher the value of the density indicators is, the higher the value of the serviceability index is. An exclusion from this trend is observed in the correlation of kindergartens' serviceability index with OSR, where the Pearson correlation coefficient (R) is negative.
- All the drawn correlations are statistically significant with a p-value < .001.

- The density indicators for demographic data, KIDd and POPd, have the strongest correlations with kindergartens' serviceability index compared to other independent variables within 10-minute walking distance. Both KIDd and POPd have an R2 value of .397.
- The indicators that refer to the functional characteristics of the built environment but also implicitly relate to the possible concentration of residents, i.e. floor area ratio for residential use (FARre) and dwelling densities (DWd), have slightly lower R^2 scores of .360 and .336, respectively.
- From the density indicators, explicitly to the spatial parameters of the built environment, the highest correlation between kindergartens' serviceability index is identified with the network density (ND) with R^2 = .384. An almost equal correlation is indicated with the interconnected indicators of the density of network intersections, gross space index (GSI) and open space ratio (OSR) with R^2 = .372. The floor area ratio (FAR) depicts a slightly poorer correlation with the serviceability index, R^2 = .281.
- A weak correlation of the serviceability index is identified with the floor area ratio for other uses (FARoth), R^2 = .073. This score indicates the spatial logic that kindergartens do not seem to be located within 10-minute walking isochrones of industrial, logistical and monofunctional commercial districts. This makes any potential trips between them by foot highly unlikely.

Based on the extracted results, it is worth outlining that the correlations between the kindergartens' serviceability index and the density indicators do not vary significantly, and R^2 is mainly concentrated between .336 and .397, excluding the correlations with FAR and FARoth. From the theoretical perspectives presented in *Section 2.1*, we can confirm that the concentration of people, expressed explicitly through POPd and KIDd and implicitly through DWd and FARre, have a distinctive correlation with the available kindergarten provisions. This illustrates that the examined service of interest in the Stavanger region tends to be generally distributed and organised with appropriate consideration of where people live while aiming to secure pedestrian access within 10 minutes.

4.3 Travel modes to physically access kindergartens in the Stavanger region

The following section presents the data collected concerning the escort trips to and from the observed kindergartens. As presented in *Section 3*, the study employs first-hand observations to register the travel modes concerning five facilities located in areas representing Stavanger's diversity of built environments concerning the GSI density indicator (see Section 3.3.1). *Table 7* illustrates the results of the observations, indicating the highest percentage of parents using cars to escort their children (66.02%), followed by walking (27.09%), cycling (6.17%) and public transport (0.60%).

Table 7
Records illustrating performed care trips in the five observed kindergartens in the Stavanger region.

OBSERVED KINDERGARTEN	TOTAL				SUMMER 2021				WINTER 2022			
	walk	cycl	car	bus	Walk	cycl	car	bus	walk	cycl	car	bus
Læringsverkst. barnehage Jåsund	21.29 (33)	1.29 (2)	76.77 (119)	0.65 (1)	17.57 (13)	1.35 (1)	79.73 (59)	1.35 (1)	24.69 (20)	1.23 (1)	74.07 (60)	0.00 (0)
Kreativ barnehage Bogafjell	16.94 (31)	9.84 (18)	72.68 (133)	0.00 (0)	13.39 (15)	9.82 (11)	76.79 (86)	0.00 (0)	22.54 (16)	9.86 (7)	66.20 (47)	0.00 (0)
Forus privat barne-hage	0.00 (0)	2.25 (5)	95.95 (213)	1.80 (4)	0.00 (0)	0.97 (1)	97.09 (100)	1.94 (2)	0.00 (0)	3.36 (4)	94.96 (113)	1.68 (2)
Kampen barnehage	44.07 (52)	15.25 (18)	40.68 (48)	0.00 (0)	49.15 (29)	15.25 (9)	35.59 (21)	0.00 (0)	38.98 (23)	15.25 (9)	45.76 (27)	0.00 (0)
Læringsverkst. barnehage Lervig Brygge	72.48 (108)	5.37 (8)	22.15 (33)	0.00 (0)	76.19 (64)	5.95 (5)	17.86 (15)	0.00 (0)	67.69 (44)	4.62 (3)	27.69 (18)	0.00 (0)
All kindergartens	27.09 (224)	6.17 (51)	66.02 (546)	0.60 (5)	28.01 (121)	6.25 (27)	65.05 (281)	0.69 (3)	26.08 (103)	6.08 (24)	67.09 (265)	0.51 (2)

We can outline some statements by comparing these observations and the characteristics of the built environment around the examined kindergartens concerning the concentrations of buildings and housing. First and foremost, based on the observed cases, we can outline that the lower the GSI of a specific area is, the higher the percentage of escort trips performed by car. This claim is supported by the results from all kindergartens, excluding the deviant case of *Forus privat barnehage*, positioned in an area characterised by a vast amount of office space and almost no housing within its vicinity of 10-minute walking. However, looking at the other four cases, we can identify an increasing percentage of car usage for escort trips as follows: Læringsverkst. barnehage in Lervig Brygge (22.15%), Kampen barnehage (40.68%), Kreative barnehage in Bogafjell (72.68%) and Læringsverkst. barnehage in Jåsund (76.77%). These values are in a complete regression with the spatial densities of the built environment around the facilities observed, expressed through GSI with values of 0.213, 0.175, 0.111 and 0.063, respectively.

We can also report that, for the examined cases, the more monofunctional a residential neighbourhood is, the higher the percentage of people who choose to cycle compared to walking. This is observed in both groups of settings. In the suburban cases, there is a considerably higher percentage of cycling to Kreative barnehage Bogafjell (9.84%) in comparison to Læringsverkst. barnehage in Jåsund (1.29%), while the walking percentages are 16.94% to 21.29%, respectively. This pattern replicates in the case of the areas closer to the urban core, where 15.25% cycle to Kampen barnehage compared to 5.37% to Læringsverkst. barnehage in Lervig Brygge. In contrast, 44.07% walk to the former facility, while 72.48% escort their kids by foot to the latter.

Weather conditions do not significantly influence travel choices in the case of the recorded escorting trips. The aggregated results indicate a slight difference in favour of using cars in winter (67.09%) compared to summer (65.05%). The figures suggest that this deviation is at the expense of the percentage of people walking from and to kindergartens, where an opposite tendency is observed, i.e. 26.08% walk in the winter, while 28.01% in the summer.

5. Discussion

The presented study proposes a mixed-method approach to measure the relationship between built environment densities and accessibility at a local scale. We focus on kindergartens in the Stavanger region and adopt the 10-minute city concept to pursue this goal. The study involves three steps: (1) we estimate kindergartens' serviceability index through GIS-based analyses in the Stavanger Region; (2) we apply statistical techniques to quantify the relationship between urban densities and the kindergarten serviceability as a function of accessibility; and (3) we conduct first-hand observations to determine users' preferred mobility modes to access five selected facilities.

The study analyses the potential to access a kindergarten within 10 minutes of walking. In this regard, the proposed method aims to build upon the works of Calafiore et al. (2021), Hosford et al. (2022) and Kesarovski & Hernández-Palacio (2022). In their studies, these groups of authors develop approaches to quantify accessibility to urban services by active mobility modes and reveal spatial imbalances within the framework of 20-/15-/10-minute city concepts. This research focuses on a single type of amenity, i.e., kindergartens. Also, we incorporate additional details, such as the capacity of the individual kindergartens. In this way, the analysis offers an enhanced capability of measuring serviceability since each object possesses a specific weight in the estimation, i.e. the number of kids registered. This approach can be applied to other services and contexts if the necessary datasets are available. In this regard, the study adds to the methodological progress of supporting the application of the 20-/15-/10-minute cities as a robust driving force for urban transformations (Capasso Da Silva et al., 2020; Dunning et al., 2021; Levinson, 2020; McNeil, 2011).

The applied method also quantitatively explores whether serviceability potential correlates with spatial densities and demographic characteristics. The results demonstrate that in the Stavanger Region, the availability of kindergartens is better in areas with higher concentrations of people (POPd and KIDd). This finding is logical and aligns with the literature on the topic, discussed in *Section 2.1* (Calafiore et al., 2021; Hosford et al., 2022; Kesarovski & Hernández-Palacio, 2022; Shi et al., 2020; Um et al., 2009). Additionally, the statistical correlations highlight the importance of built environment characteristics that enhance spatial connectivity, such as ND and GSI (see *Table 6*). It is worth underlining that the strong correlation between serviceability and ND highlights the significance of network segments' concentration. Despite the limitation of examining a single case, this finding is in line with the postulates about the role of street networks in cities. The topic is introduced in *Section 2.1* under several perspectives, such as space syntax (Hillier et al., 1993; Ye & Van Nes, 2013) and other GIS urban morphology-related studies (Porta et al., 2006; Araldi & Fusco, 2019; Calafiore et al., 2021; Kesarovski & Hernández-Palacio, 2022).

Although with a limited number of first-hand observations, the study also incorporates fieldwork to examine whether there is a greater potential for walking in denser urban environments. From a methodological perspective, this approach is a simple and easy-to-replicate technique to study travel choices without relying on self-reported data from surveys traditionally employed (Grazi et al., 2008; Næss et al., 2017). However, the approach has a limitation regarding the depth of investigating travel behaviour since the trip's points of origin and further destination(s) are not considered. If, instead of exploring travel potential as in this study, the focal research topic is the causal mechanism behind individual travel behaviour, it is worth considering complementing the approach with more in-depth data collection techniques, such as surveys and interviews. As discussed in *Section 2.2*, researching escort trips is particularly challenging because these trips can be embedded in the travelling routines of the accompanying adults, causing distortions. However, when supported by GIS-based analyses, the results of such field observations can shed light on escort trips to specific facilities. Considering the substantial number of children attending kindergartens in Norway, the proposed approach can contribute to studying mobility choices in connection to the built environment.

As this study focuses on 10-minute isochrones by foot, the results imply that denser urban areas incentivise walking (and cycling) to kindergartens. The fieldwork confirms this statement, where we observe less car usage and much higher shares of active mobility modes in denser areas closer to Stavanger's urban core (see *Table 7*). These findings provide relevant outputs for urban practitioners and contribute toward identifying functional service ranges by active mobility modes in Norwegian cities, as explored by Øksenholt et al. (2016). By visually representing the aggregated serviceability index (see *Figure 2*), the method also proposes a practical tool to illustrate the capacities of any network of urban services. This can aid experts in improving existing provisions and achieving a balanced service supply in urban regions.

6. Conclusion

The research method we present in this article goes beyond studying accessibility to urban amenities. The approach aggregates the serviceability index of a given area and incorporates spatial and demographic aspects with limited fieldwork observations of travel modes. The method is flexible as it allows adjusting any researched services, the time thresholds, the mobility modes, or the spatial context. The fieldwork technique is also easy to replicate at any facility and context without requiring complex preparations, data protection restrictions, or expert knowledge to generate non-self-reported data. This methodological approach is the main contribution of this study.

On the other hand, the research approach meets certain limitations that need to be recognised. First, the GIS serviceability estimations do not consider the specifics regarding individual walking speeds to perform the escort trips from and to kindergartens. These can vary significantly based on the escorted kid's age and the local walking conditions. A single average speed of 4.86 km/h can distort the outcomes concerning the estimated serviceability index for the Stavanger region.

Second, the performed linear regressions support the discussed theoretical implications regarding the relationship between densities, provided service capacities and accessibility, but incorporating other built environment details may become necessary. Aspects such as average block sizes, sidewalk width, and the design of the cycling infrastructure can provide further depth considering the relationship between the local built environment and travel behaviour.

Third, the first-hand observations are time-demanding and challenging to conduct at a more significant number of facilities for an extended period. In addition, it is worth mentioning that the accuracy of measuring public transport users can be unreliable. This number is aggregated during the fieldwork by observing the closest bus stop to the respective kindergartens. Therefore, some users counted as pedestrians could have used public transport but arrived at a bus stop beyond the immediate vicinity of the respective kindergartens.

Fourth, when analysing the linear regression to explain the estimated serviceability index, it is worthwhile to consider incorporating additional indicators such as job densities. This is because escort trips can often become integrated with work trips for the accompanying adults, adding complexity to the analysis.

Fifth, surveys within the observed facilities and, or interviews with the escorting adults can further enrich the approach. By incorporating qualitative information regarding transport opportunities, constraints, and possibilities at hand for the escorting adult, the method can better reflect on the causal mechanisms behind mobility choices and produce more comprehensive insights regarding the built environment's impact on travel behaviour. We also want to highlight that the home-office policy introduced during the COVID-19 pandemic may have increased the number of pedestrian escort trips, given that parents are likely to live within walkable distances from kindergartens. However, revealing if this fact has had a significant influence will require doing new observations and comparing them, a task for a future study.

Experimenting with these notions can reveal further details regarding the method's potential and limitations to provide coherent practical inputs towards concepts such as the 20, 15, and 10-minute city. This way, the proposed research approach can contribute toward optimising the relationship between the built environment and the degree of urban services provision across specific regions as an operational framework to promote sustainable mobility.

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Biographical information

Fabio Hernández Palacio
Department of Safety, Economics, and Planning
Faculty of Science and Technology
University of Stavanger
Address: Otaniementie Kjell Arholms gate 41
4021 Stavanger, Norway
Phone: +47 5183 2878
E-mail: fabio.hernandez@uis.no

Fabio Hernández Palacio is an associate professor at the Department of Security, Economics, and Planning, teaching in the programme city and regional planning. His research interests revolve around how the built environment can influence sustainability, looking at urban quality, urban form, urban density, and densification. He has studied different features of the sustainable city, including densification as a planning strategy, the relationship between density and transport, urban quality and sustainability, and the transition towards more sustainable cities.

Biographical information

Todor Kesarovski
Department of Safety, Economics, and Planning, University of Stavanger,
Address: Nedre Banegate 6, apt. 9, 4024 Stavanger, Norway
Phone: +47 407 29 236
E-mail: todor.m.kesarovski@uis.no

Todor Kesarovski is a PhD candidate and lecturer at the Department of Safety, Economics, and Planning at the University of Stavanger, where he develops the research project "Optimising Urban Densities for Sustainable Cities". In his work, he explores the potential to support advances in modelling urban environme-nts and enhance densification strategies through big data and GIS analytical techniques. Before joining the University of Stavanger, Todor gained academic knowledge at TU Delft and the University of Amsterdam as a student graduate, teaching assistant and junior researcher.