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Evaluation of social facilities coverage: A case study of Sofia city

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Abstract: In order to aid the decision making process related to the provision of public services as to maximize the benefits for society, it is crucial to evaluate the current social facilities demand in terms of spatial distribution and access. The paper aims to solve this problem by proposing a method for automated assessment of the coverage of public services within an urban region using a capacitated graph. The methodology abstracts residential buildings into demand nodes and public service buildings into supply nodes within a graph and then uses shortest distance calculations in order to balance the two, while prioritizing residential buildings based on distance.
The paper is focused on creating a general pipeline that can be used on any type of public services, as long as a certain geospatial and demographic data are available. The method is described without referencing specific tools, but focusing on the general procedure. The procedure is then applied to the whole city of Sofia, focusing on assessing the coverage of kindergartens using the 15 minutes walking distance, followed by a brief discussion of results.

Keywords: Social facilities coverage, supply and demand estimation, network analysis, walkability access

1. INTRODUCTION

The location of social infrastructure is a critical component of urban planning and design that affects the everyday life of the citizens. It is a complex system of facilities such as schools, kindergartens, parks, hospitals, post offices, etc. The planning of social infrastructure needs to consider many factors and criteria such as distance from demand points, population density, cost, distribution of current infrastructure and changing needs of the local community. Thus, comprehensive models and tools to support decision-making are required to achieve a sufficient level of social infrastructure.

The covering problem is the most popular one among social infrastructure location models [Farahani et al. 2012]. It attracts a lot of research efforts due to its applicability to improve the living conditions in urban areas, especially in large cities. Most covering problems are based on the requirement that the citizen should be served by at least one facility within a given distance. Although variety solutions of such problems exist, the walkability concept is preferred for implementation due to the direct impact on a healthy lifestyle. The walkable cities provide social facilities that are accessible within walking distance. The covering problem considers the capacity of facilities, residents' demand, and the distance between the two via a pedestrian street network. It can be solved by applying the Maximum Population Shortest Path method to find a path in a network such that the length of the path is minimized, and the coverage of the population is maximized [Boffey and Narula 1998].

This paper tackles the covering problems in facility location by proposing a comprehensive method for evaluation of the kindergartens and nursery coverage regarding accessibility. It answers the following research questions:

- What is the supply and demand gap of childcare facilities at a city level?
- What are the differences in the supply and demand of kindergartens and nurseries in various city areas?

The proposed method is automated in a tool, which takes as inputs the childcare facilities, the residential buildings and the pedestrian street network along with demographic data and rules for establishing maximum service capacity in order to evaluate the public building coverage. It is intended to be used for any type of public service assessment and for any geographic region while being used interactively by domain specialists.

The rest of the paper is organized as follows. Section 2 provides a background information about the problem and area of study. Section 3 highlights the related works. Section 4 presents the proposed approach for estimation of social facilities coverage, while Section 5 discusses the

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results. Finally, section 6 concludes the paper and outlines future work.

2. BACKGROUND

The proposed method has been developed to assess the coverage of kindergarten and nursery services within the city of Sofia, while considering a 15 minute maximum walking distance. The city covers a land of around 5 723 km^2 and has around 1.3 million inhabitants. It is the largest city in Bulgaria and one of the largest on the Balkans, increasing in population by around 1 % each year.

Sofia is experiencing a shortage of social facilities such as kindergartens, schools and senior care homes. This is due to three main reasons as follows:

- Closure of childcare facilities and their assignment to other functions in the late 1990s, due to negative demographic dynamics;
- Mass construction of buildings, especially in the southern neighbourhoods, without providing all the necessary infrastructure, including kindergartens and nurseries;
- Population growth in the capital over the past 15 years.

Thus, in the latter application for childcare in 2021 about 12,000 children did not succeed to find a place in a kindergarten or a nursery. To deal with this problem, Sofia Municipality has adopted a "Program for the construction of kindergartens 2021-2023", which is expected to solve the problem of local shortages in a very short time.

3. RELATED WORK

3.1 Child pedestrians and local infrastructure

Children experience neighbourhoods differently than adults; as such Gielen et al. [2004] use the term textitchild pedestrian to discuss the risk of injuries for children using the streets. Walkability in neighbourhoods must not only focus on the adults but also the needs of the textitchild pedestrian. With a large proportion of children walking to school, the rates of *child pedestrian* injuries are quite high in urban areas. Children who walk to school are more active than those who do not Kerr et al. [2006].

Gielen et al. [2004] conducted a descriptive study on parents (n=732) of kids in different elementary schools belonging to neighbourhoods with varying income and *child pedestrian* injury risks. They found that parents in lower-income neighbourhoods reported the highest rates of unpleasant walking experiences, further emphasising the importance of promoting physical activity in urban neighbourhoods especially focusing on children's injury risk while walking in lower-income neighbourhoods. Kerr et al. [2006] found similar results in their study exploring active commuting to school on children's behaviour (n=259). Concerning the income level of the background, they found that income was not related to commuting behaviour. However, among neighbourhoods with high walkability, the lower-income neighbourhoods showed the greatest concerns with child safety. In both these studies, it was the parents' perception of the neighbourhood that played a large role in the experience of the *child pedestrian*.

3.2 Evaluation of childcare service coverage

There are broadly two approaches to social infrastructure planning, a population based approach and an access based approach [Yhee et al. 2021]. Population based approaches use grid based catchment areas to determine the population serviced with social infrastructure. The access based approach uses Geographic Information system (GIS) based tools to evaluate the geographic access to facilities. Older studies such as van Ham and Mulder [2005] have analysed the access to childcare in the Netherlands through the population based approach and explored its relationship to the mother's participation in the labour force. The authors describe *good geographical access* to childcare as the number of childcare slots per 100 children in an area within 10 minutes of travelling from their residences. The access is calculated using the maximum travelling time and mode of transport used. The location of the residences vis-a-vis the spatial configuration of childcare facilities and the travelling time of mothers to facilities are considered. he access to childcare positively affects the probability of being engaged in paid employment. Furthermore, one childcare slot per 100 children increased the offs of paid employment among mothers by 2.2 %, a stronger effect even compared to the effect of level of education. A similar study by Kawabata [2014] is conducted in Tokyo to explore the lack of access to childcare facilities and its relationship to women's participation in the labour market through. The lack of access to childcare facilities is explained with the lack of supply and the geographical mismatch between the supply and demand of childcare. The study uses GIS methods to evaluate childcare services across the 23 wards of Tokyo. The supply of childcare centres is calculated using three types of childcare capacities. The distances are calculated using road network data. The thresholds for the childcare catchment areas are defined both in time and distance; 10, 15 and 20 min walking time for 500, 750 and 1000 m. The existence of the geographical mismatch between the supply and demand of childcare services is shown. The access to childcare has a higher association with attaining preferred employment among women with preschool-aged children. More recent studies such as Yhee et al. [2021] have updated the access based approach by incorporating real-time navigation services to provide more accurate data on access and navigation to add further accuracy to past methods.

In a 2017 study, Davern et al. [2017] use spatial measures to explore the relationship of social infrastructure to health and wellbeing based on a 2011 survey on health (n=24,900). At the time of the study, they noted that GIS was not always used to assess social infrastructure and planning. The authors considered four domains of social infrastructure – health and social facilities, early years, culture and leisure and community centres. The maximum distance to social infrastructure was calculated using the greatest distance that each survey participant needed to travel to access any particular social facility. Three different buffer distances were assessed (800, 1200 and 1600 m). Having a single service within 1600 m was not the most beneficial; rather, multiple mixed services within 800 m was the most beneficial to subjective well being. These results support previous studies endorsing the increase of local facilities within a 20 min walk of the residences for improved subjective wellbeing. In a more recent Finnish study by Weckroth et al. [2022] a population based approach is applied to explore a national health survey (n=26,000) across 3300 postal code areas.The study looked at the relationship between neighbourhood characteristics and perceived quality of life. The results shed light on the contrasting urban phenomena of the *urban happiness penalty*. More positive quality of life effects are observed in rural living rather than the urban context. However, an increased share of residents with tertiary education in a neighbourhood positively affected the quality of life.

Related to addressing the urban supply and demand of amenities, Lee et al. [2018] states that there is overwhelming support for walkable access to amenities among younger residents in the US. Lee et al. [2018] explores the relationship between zoning, land use and urban form using factor analysis of urban-form and street characteristic variables among others. Other clustering and regression methods are used to derive a walkable score and assess the relationship between walkable access to amenities and similar groups of urban characteristics. The approach shows that single-family housing and low-density developments run counter to the walkability goal.

Dogan et al. [2020a] further introduce *amenityscore* as an indicator designed to balance the more popular walkability indicators by measuring the difference between the supply and demand for a particular amenity to assess the utilisation of said amenity in the neighbourhood. Other indicators such as accessibility index are introduced by Yhee et al. [2021]. There are, however, very few tools targeted towards facilitating such analysis for architects and urban planners. One such tool currently in development [Dogan et al. 2020b] combines GIS methods of spatial analysis with the 3D modelling tool Grasshopper [Rutten et al. 2007] to create an urban planning support tool.

A large body of literature in the health sciences focuses on the health and wellbeing aspects of walkability access to local infrastructure [Yhee et al. 2021], especially in children [Gielen et al. 2004, Kerr et al. 2006, Badland et al. 2009]. The extended consequences on quality of life and increased productivity for the population are also clear [van Ham and Mulder 2005, Kawabata 2014]. However, analytical evidence based on spatial analysis has gained prominence due to increased access to computation tools and methods. One key limitation of past studies however, is the lack of appropriate digital tools and methods to perform such analyses. The use of modern GIS tools and methods can help study the relationships between walkability and the built environment in greater detail [Badland et al. 2009]. The literature shows that new methods to incorporate spatial analysis to support the planning of socially sustainable neighbourhoods are welcome. There is also a need for planning support tools focused at urban designers and policy makers.

4. APPROACH

This paper proposes an automated access based approach for assessment of social facility coverage. This method can be considered as a network flow problem where social facilities are considered as supply nodes and residential buildings as demand nodes. Supply and demand are then balanced based on walking distance and capacity.

4.1 Assumptions

The proposed approach relies on building and other land-use data. It implies assumptions of choice, social service requirements and mode of transport as discussed below:

- The residential buildings are prioritized solely based on their proximity to the closest social facility without taking into account additional social-economic factors.
- The residents only use the pedestrian walkways to get to a social facility and they always prefer the closest available one. No other modes of transport are considered and it is assumed that all citizens walk at the same speed.
- The characteristics of social facilities such as year of construction and quality of service are not considered. Thus, the residents have no preference for one facility over the other. Only the space provided by a facility is of interest.
- The number of residents is known either from a direct survey or inferred by different means.
- The requirement for floor area per individual is Xm^2. Thus, the demand is expressed in terms of floor area.
- The residential buildings and social facilities are integrated into the pedestrian network based on the closest node of the Euclidean distance.

4.2 Method

The proposed method aims to evaluate the coverage of social facilities within a study region. Using the above assumptions it solves the supply and demand problem by calculating the shortest distances between each building and its closest social facility based on the following steps:

(1) Input datasets for pedestrian network, social facilities and residential buildings along with their attributes;
(2) Calculate the supply and demand for each node;
(3) Create a graph from the pedestrian network and snip buildings along with their attributes;
(4) Calculate the shortest distance between each demand node and its closest supply node;
(5) Sort the resulting list by distance;
(6) Subtract the demand from the supply for each pair of nodes in the sorted list.
(7) Repeat steps 4 to 6 until no changes in the supply nodes are registered.

Inputs The model is intended to be used with only buildings and demographic data. The buildings data is required to be in standard GIS format and can be imported directly from a PostGIS database or as any standard format such as a shape or geojson file with demographic data for each building attached as an attribute.

Rules about the gross floor area per person are also required and should be specified based on the local legislation or domain expertise. Three input datasets are needed: (1) Residential buildings with an attribute specifying the number of inhabitants; (2) Social facilities with an attribute for the number of storeys; and (3) Pedestrian network specified, either without attributes or with an attribute for traversing time.

Calculating supply and demand The supply and demand is estimated on the basis of available and required floor area of social facilities. The available floor area is the gross floor area of the social facilities. The required gross floor area is calculated on the basis of the number of individuals intended to used the social facilities multiplied by the required floor area per individual.

Creating graph network The pedestrian network is transformed to a graph, with line segments corresponding to edges and intersections corresponding to nodes. The weight of the edges present the transverse time for each line segment.

The residential buildings and social facilities are snipped to the closest node in the graph with their aggregated values of demand and supply attributes. The snipping is based on the Euclidean distance between the residential buildings and social facilities, and the corresponding nodes.

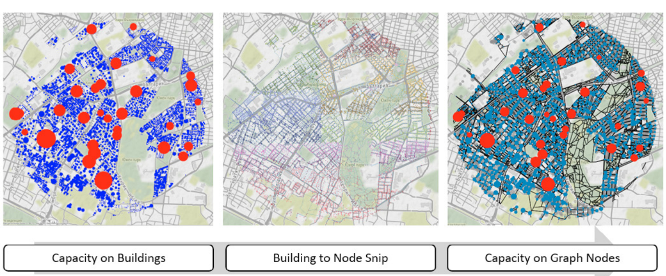

Fig. 1. Process of creating a graph network

Coverage Estimation Algorithm The previous preprocessing steps output a graph and a geospatial layer. The graph layer is derived from the geometry of the street network, with the edges being associated to line segments and the nodes associated with the ends of those segments. As discussed in the previous section the geospatial objects are snipped to nodes in the graph layer, with their indices serving as an information bridge between the two.

The core algorithm uses a multi-source Dijkstra algorithm to calculate the shortest distance from each demand node to their closest supply node with a DataFrame storing the demand and supply node tuples along with the Manhattan distance between the two, where supply nodes are defined as nodes having a supply larger than a predefined value ϵ (for numeric stability), while the demand nodes are nodes that have a non-zero demand.

Then for each row in the stored list the value of the demand node is subtracted from the value of the supply node with the values of the graph being updated accordingly. This is done sequentially for all rows only if the supply is larger than the demand, otherwise it is assumed that the public services belonging to the supply node cannot take the demand and are not updated.

As the residential buildings and public services, which exist as objects in the geospatial layer, are referenced in the graph layer via their indexes listed as node attributes, after each node balancing the demand of the residential buildings and the supply of the public services are updated as well.

This means that if the value of the demand node is changed to 0, then the demand of all residential buildings referenced in that node will also change to 0 and if the value of a supply node decreased then it will be taken out of the supply of the first referenced public service.

Additionally, in order to reference the residential buildings to the corresponding public services when a demand node is serviced by a supply node the indices of the corresponding residential buildings are assigned to a column in the corresponding public service building in the geospatial layer.

The distances themselves are referenced as an attribute for every residential building during this procedure, while neglecting the euclidean distances from nodes to geospatial objects.

This procedure essentially attempts to allocate all residential buildings to their closest facility while making sure their maximum capacity is not exceeded.

However, it has been observed that it can't be expected that all residential buildings will be serviced by the closest supplier and additional iterations are required in order to allocate residential buildings to a more distant public service. Therefore, the whole procedure is iterated until no change in the supply and demand of the system is observed.

Graphical representation The process is shown diagrammatically in Fig. 2 where supply nodes are shown in red and demand nodes in blue. The first figure represents the initial condition of the system whereas the second shows the balanced graph after the first allocation round. It can be seen in the second figure that many demand nodes have not been allocated to their first choice and an additional iteration is required to recalculate the shortest distances for the remaining nodes. The third figure presents the final result where the supply of the system is exhausted with only minuscule demand being leftover.

In general this algorithm has been tested both on the whole city of Sofia and on multiple smaller sub-regions within the city and it has been observed that given enough iterations either the supply runs out before the demand or visa versa with some cases having leftover supply and demand due to all distances exceeding the walkability limit. This helps classify the system as having enough capacity, lacking capacity or not being well positioned.

Fig. 2. Balance of the supply and demand within a graph of a randomly selected region

Outputs The algorithm results in two new datasets.

- A copy of the input residential building dataset enriched with information regarding the time it takes to get to a service by foot and the index of the social facility that is servicing each residential building.
- A copy of the social facility dataset enriched with information about the total serviced demand and the leftover capacity. If more than one demand column exists then both are included as attributes.

5. RESULTS

The proposed method is applied to a kindergarten coverage assessment of Sofia city. The geometries of the kindergarten are provided and all residential buildings within the city are given as points with attributes of demographic data. Each residential building has attributes, presenting the number of children 0 to 3 years old and 3 to 6 years old. The pedestrian network has traverse time attribute specified for each line segment.

It is assumed that 50% of the children 0 to 3 years old and 90% of children 3 to 6 years old are expected to receive a child care. Additionally, 20 m^2 of kindergarten floor area is required for each child that is in the ages 0 to 3 and 25 m^2 for children ages 3 to 6. A walking distance of 15 min is given as a cutoff to the shortest path calculations.

As discussed in the previous section the algorithm employs an iterative procedure that matches residential buildings to the closest available public service. The results of this iterative procedure applied on the whole city of Sofia are presented in Fig. 3.

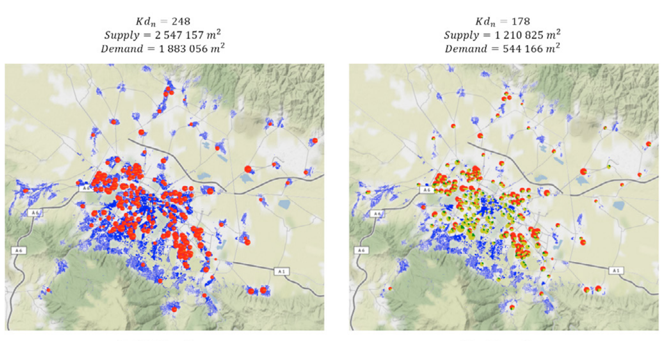

Fig. 3. Initial Capacity of the system

In the first figure all residential buildings and kindergartens are presented on the map. In the second map the residential buildings with satisfied demand have been removed and the filled supply in the kindergartens has been represented in a pie chart, with yellow presenting the m^2 allocated for 3-6 year olds, green for 0-3 year olds and red showing the remaining leftover capacity.

The initial number of kindergartens with capacity is 248 and through the iteration it drops to 178, with the total supply in the system dropping from $2.55 * 10^6$ to $1.21 * 10^6$ with the demand dropping from $1.88 * 10^6$ to $0.54 * 10^6$.

It can be seen in Fig. 4 the algorithm converges almost completely on the second iteration and most children that do get served actually go to their closest kindergarten. The convergence graph also agrees with Fig. 3.

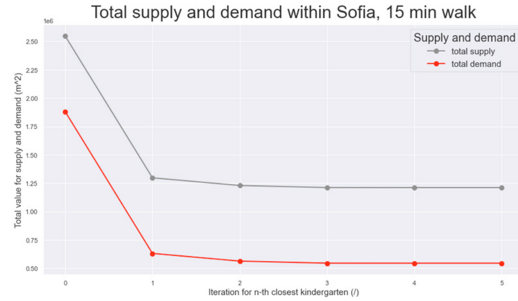

Fig. 4. Convergence curve for 15 minute walking distance

It is apparent that even though neither the supply and demand are exhausted the algorithm converges. This is because the remainder of residential buildings live further than a 15 minute walking time from the closest kindergarten and therefore are not serviced under that constraint. This points to a poor allocation of kindergartens with respect to walkability considerations.

Thus, the algorithm applied to the following dataset shows that even though there is more supply of kindergarten space then demand for it, because it is poorly allocated 23 195 children are further than a walking distance from those facilities and will require transport to get to them with most buildings allocated close to the city center and the outskirts of the city near Vitosha mountain.

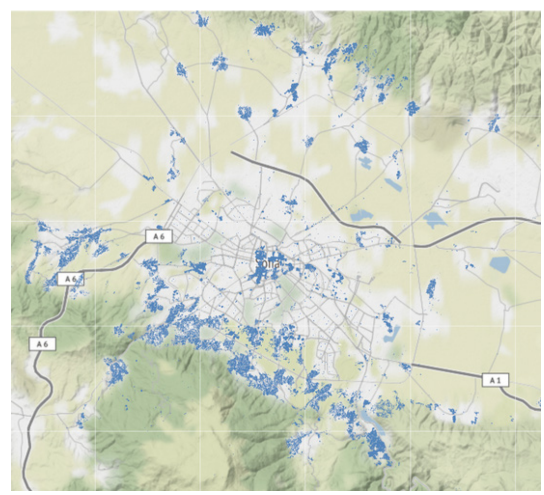

Fig. 5. Residential buildings lacking accessibility to kindergarten services within 15 minutes walking time

Finally, for children that do live within a 15 minute walking distance further analysis has been performed. Data about the walking times for all residential building has been collected as shown in Fig. 6.

It can be shown that the distribution of walking times for all residential buildings has a mean of $\mu = 6.85$ minutes and standard deviation $\sigma = 3.81$ minutes, with a decreasing tail as n goes to infinity.

This entails that while there is a lot of residential buildings outside the walking range within it the average walking distance is around 7 minutes and a maximum probability at around 4 minutes, meaning a relatively short walk.

All of this information can be used in order to guide new construction of public services and to prioritize the most distant homes while considering not only single values such as maximum walking time but the distribution as a whole.

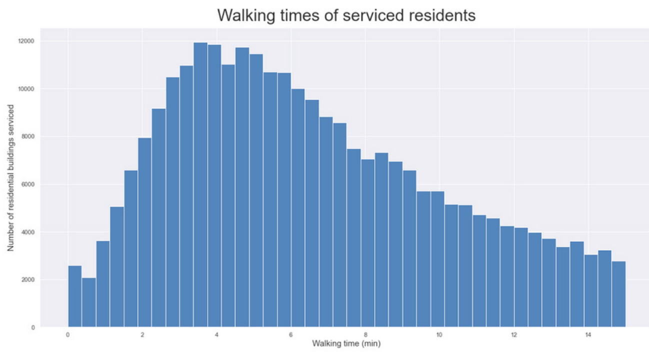

Fig. 6. Walking time distribution

6. CONCLUSION AND FUTURE WORK

The proposed method can be used by decision-makers or planning professionals to evaluate social facilities coverage within a region. Based on the results new facilities can be located more efficient to minimize costs and to increase the city walkability, while over-capacitated kindergartens can be restructured. The obtained results are valuable for society as a whole.

In the case of Sofia, it has been seen that areas with increased interest from private real estate investors are the least serviced by kindergartens. The use case also highlights that the problem comes from poor service distribution with 63203 buildings lacking walking access to facilities, even though the total capacity if kindergartens is enough to cover the needs. The lack of walking accessibility of social facilities force people look for other means of mobility. This in turn increases the traffic causing congestions and air pollution. The overall performance of the city is reduced due to wasted time and resources.

Future work includes development of an approach for allocation of new social facilities to satisfy the demand gap. The proposed method will be reused to a large extend for evaluation of coverage of other social facilities.

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