A Network Flow Model for the Analysis of Green Spaces in Urban Areas

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Abstract

Green spaces in urban areas offer great possibilities of recreation, provided that they are easily accessible. Therefore, an ideal city should offer large green spaces close to where its residents live. Although there are several measures for the assessment of urban green spaces, the existing measures usually focus either on the total size of green spaces or on their accessibility. Hence, in this paper, we present a new methodology for assessing green-space provision and accessibility in an integrated way. The core of our methodology is an algorithm based on linear programming that computes an optimal assignment between residential areas and green spaces. In a basic setting, it assigns a green space of a prescribed size exclusively to each resident such that the average distance between residents and assigned green spaces is minimized. We contribute a detailed presentation on how to engineer an assignment-based method such that it yields reasonable results (e.g., by considering distances in the road network) and becomes efficient enough for the analysis of large metropolitan areas (e.g., we were able to process an instance of Berlin with about 130 000 polygons representing green spaces, 18 000 polygons representing residential areas, and 6 million road segments). Furthermore, we show that the optimal assignments resulting from our method enable a subsequent analysis that reveals both interesting global properties of a city as well as spatial patterns. For example, our method allows us to identify neighborhoods with a shortage of green spaces, which will help spatial planners in their decision making.

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1 Introduction

The existence as well as the spatial distribution of green spaces in a city have a large impact on the quality of life. Therefore, spatial planners are interested in quantitative measures for the assessment of cities with respect to their green spaces. Different indicators have been suggested for this purpose. In particular, indicators for *green-space accessibility* and *green-space provision* have been described [9]. We argue, however, that the one cannot reasonably be assessed without the other. If, for example, a small green-space exists in the center of a city, it may be accessible for many residents but not at all sufficient to satisfy their demand. Large green spaces at the boundary of a city that are difficult to access, on the other hand, may lead to a positive assessment with respect to green-space provision, although they are of limited use for the city's residents. Therefore, we introduce a new methodology to analyze green-space accessibility and green-space provision in an integrated way.

Our basic idea is to assign a certain amount of green space *exclusively* to each resident, meaning that each green space can supply only a limited number of residents and, thus, is assumed to have a certain *capacity*. We compute the assignments such that a prescribed per-capita demand is satisfied for each resident and the average distance in a road network between residents and assigned green spaces is minimized. We use this *average distance to assigned green spaces* (i.e., the objective value of the solution) as a global quality measure and approximation for the accessibility of the green spaces. For the sake of simplicity, we do not require each resident to be assigned to a single green space but consider the population of a residential area as a quantity that can be split into arbitrary fractions which can be assigned to different green spaces. Such assignments are modeled as a flow from the residential areas via the road network to the green spaces.

Although we consider the average distance to assigned green spaces particularly interesting, we will introduce a more general objective function that allows us to distinguish different types of green spaces and residential areas of different demands. Besides, we will show that the solutions that we obtain provide interesting information on spatial patterns within a city. In particular, since the result of our method depends on several parameters, such as the per-capita demand, we are interested in studying the influence of these parameters on an optimal assignment. A green space far away from any residential area, for example, will be assigned to no resident unless the per-capita demand is set to a very high value. Hence, we can measure the importance of a green space by identifying the smallest per-capita demand for which it is used in the assignment. By visualizing the green spaces with colors representing those values, we obtain a map that highlights important green spaces.

To put our general idea to practice, several design decisions have to be made and technical obstacles have to be overcome. For example, the data set has to be reasonably selected to include all relevant green spaces. Furthermore, green spaces and residential areas are usually given as sets of isolated polygons with no direct connection to the segments of a road data set and, thus, additional links have to be established. The number of residents a green space can satisfy does not only depend on the size of the green space but also on its type (e.g., parks have higher recreational values than forests) and, therefore, needs to be modeled adequately. Moreover, since the polygons representing residential areas and green spaces may be too large and complex to reasonably argue about the distances between them, it may be necessary to partition the polygons into smaller units. All of these aspects are considered in our method in the sense that it offers parameters that should be set by domain experts (e.g., spatial planners). We discuss in detail how these parameters are considered in our method. However, we use rather basic methods and parameter settings in our experiments.

In algorithmic terms, we adapt the *transportation problem* [13], which has been studied frequently to decide how to ship a commodity from a set of suppliers to a set of consumers [8]. For assessing green spaces, however, it has not been applied yet. The transportation problem can be solved with specialized algorithms [5] or via linear programming (LP) [6]. We choose the latter since it can be implemented easily with a mathematical solver and since an LP formulation can be extended easily, for example, to incorporate additional constraints.

The rest of the paper is structured as follows. After discussing related work (Section 2), we introduce a generic network flow model that constitutes the core of our methodology (Section 3). We further present how to deploy this model overcoming several technical obstacles (Section 4) and how to use it for the analysis of green spaces (Section 5). We finally conclude the paper with a short outlook on future work (Section 6).

2 Related Work

Urban green spaces affect the quality of life in a variety of manners. In different fields, researchers stressed the significance of green space to cities considering socio-cultural (e.g., [17, 18]), medical (e.g., [2, 3]), ecological (e.g., [14, 15]), or economic aspects (e.g., [12, 19]). Consequently, there is an increasing interest in measuring and assessing the green-space supply of an urban area (e.g., [7, 10, 19]).

Baycan-Levent et al. [1] make clear that assessing the green space of a city is a complex problem. They perform an analysis on several criteria considering various aspects mentioned above. With their approach, only the green spaces of an urban area themselves are assessed without taking the residential areas into account: The sheer existence of a high-quality green space improves the rating for a city regardless of whether its residents are able to access it. But, especially for benefits arising from visiting a green space its accessibility is crucial.

Comber et al. [4] examine the green-space supply of a city with respect to its residential areas. They perform a *road-network analysis* in order to determine the accessibility of urban green spaces. With respect to the road network, they consider the percentage of citizens living within a certain radius of green spaces exceeding a minimum size. Their approach lacks the complexity of the analysis of Baycan-Levent et al. and a more differentiated global view on the situation in the city. Comber et al. detect for residential areas whether a green space of adequate size is within a certain distance d or not. If not, no further differentiation takes place: For their assessment methodology, it does not matter whether residents have to walk slightly more than d to the next suitable green space or several times the distance. In order to handle this problem, Comber et al. repeat their analysis for various settings concerning the distance to and the minimum size of the considered green spaces.

Sister et al. [16] use a road-network analysis in order to examine *park pressure*, the ratio of the number of people assigned to a park to its area. They use mean park pressure in order to assess the green-space supply of a city. Their method uses Voronoi diagrams for assigning residents. Considering the average, a positive overall rating may hide a park with immense pressure as parks in this model have unlimited capacity. Furthermore, with Voronoi diagrams, each resident is assigned to the closest green space. Sister et al. are aware of this simplification but pursued their strategy since proximity plays an important role to residents for the selection of a park to visit. Nevertheless, this assumption leads to distorted assessments. With this measure, the assessment of the green-space supply of a city can be improved by abolishing small green spaces close to residential areas in order to assign the residents to a different (slightly more distant) and, above all, more capacious green space. Improving the green-space supply by abolishing existing green spaces without replacement is counter-intuitive and, thus, on the downside of this approach.

In a recent work, Grunewald et al. [9] suggested indicators considering both green-space accessibility and provision. For accessibility, they compute the share of inhabitants living within a certain distance from green space. Concerning provision, they examine the green-space area per capita both globally and in walking distance from residential areas. A city with green spaces accessible for many but of insufficient capacity, e.g. in high-density residential areas, earns a high rating with respect to accessibility; A city with large green spaces accessible only for few, e.g. on the outskirts, gets a high provision rating. A combination of both leads to a high overall rating although the city's inhabitants are not satisfied. The problem is that Grunewald et al. rather accumulate than combine accessibility and provision criteria. In this paper, we consider green-space provision and accessibility in an integrated manner.

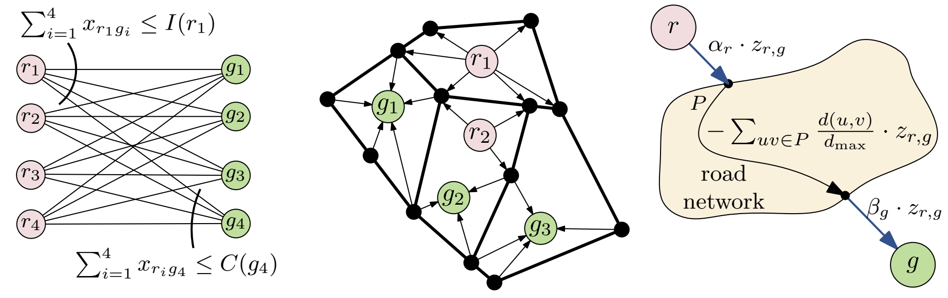
3 Methodology

In this section, we describe the core of our methodology. We first describe the underlying concepts and ideas informally (Section 3.1). Then, we present a formal model implementing these ideas (Section 3.2). This model is rather generic and allows different instantiations that can be adapted for versatile purposes. Finally, we describe a specialization of the model that assumes that residents prefer nearby green spaces (Section 3.3).

3.1 Basic Concepts and Ideas

As discussed in Section 2, several approaches have been suggested to measure and assess the supply of green space in urban areas. One of the simplest approaches is certainly computing the area of green space that is available per resident. However, this measure does not take any information about the structure of the urban area into account. Green spaces far away from residential areas contribute in the same way as green spaces easily accessible by the residents. Hence, as an alternative one may consider the average distance between residential areas and their nearest green space. This, however, ignores the restricted capacity of green spaces. For example, small parks in the city center may not serve all residents, but the typically larger green spaces outside the city boundaries may also be needed to satisfy the demand of the residents. Moreover, while both approaches break down the assessment of green space into an easily comparable number, both do not support a differentiated, spatial analysis on the distribution of green space. However, for urban planning this is precisely essential to answer questions about the importance and accessibility of particular green spaces as well as about the supply of green space to individual residential areas.

We introduce a methodology that interweaves both measures and overcomes their shortcomings. We assume that for each residential area we are given its number of residents and for each green space we are given its capacity, i.e., the maximum number of people that can be served by this area. Intuitively, larger spaces may serve more people than smaller spaces, but this number may also rely on other criteria such as the type of the green space (e.g., a park may serve more people than a forest of the same size). The overall idea of our methodology is to assign the residents of the residential areas to the green spaces such that the average *happiness* of the residents is maximized, while the capacities of the green spaces are respected. We model happiness by rating for each residential area and each green space how much the residents of the residential area prefer that particular green space. This rating typically relies on the distance between the residential area and the green space, but other factors such as the demography of the residential area and the type of the green space may be taken into account. We say a high rating causes high happiness and, altogether, aim for



(a) **(b)** **(c)**

Figure 1 Assignment Model. Residential areas are represented by red vertices and green spaces by green vertices. (a) Illustration of a generic assignment model. (b) Service network $N = (V \cup R \cup G, E \cup F)$ based on the road network $H = (V, E)$ (black vertices and fat edges), the residential areas R and the green spaces G. (c) Flow $z_{r,g}$ is transmitted from the residential area r to the green space g through the road network on the shortest path P. The flow creates the value given in Equation (7).

an assignment that maximizes the average happiness of all residents. The strength of the model lies in the possibility of applying a detailed spatial analysis on the result; we perform such an analysis in Section 5.2.

3.2 Generic Assignment Model

We now describe how we model the problem formally. We assume that we are given an urban area that consists of a set R of residential areas and a set G of green spaces. Each residential area $r \in R$ has a number $I(r)$ of residents and each green space $g \in G$ has a number $C(g)$ of residents that can be served; we call $C(g)$ the *capacity* of g. We aim to find an assignment such that no green-space capacity is exceeded and the average happiness of the residents is maximized. We formalize this as follows. For a residential area r and a green space g we interpret the triple (r, g, i) such that i residents of r are assigned to g. We call $A \subseteq R \times G \times \mathbb{R}^+$ an *assignment* for (R, G) if it maintains the supply and capacities of the residential areas and green spaces, respectively. That is, we require $\sum_{(r,g,i) \in A} i \leq I(r)$ for all $r \in R$ and $\sum_{(r,g,i) \in A} i \leq C(g)$ for all $g \in G$. However, not every assignment is equally good, but its quality may be affected by multiple criteria such as distances, the type of the green spaces, the mobility of the residents of a residential area, etc. Therefore, we introduce the rating function $h\colon R \times G \to [0, 1]$ that describes the preferences of the residents. The higher the value of $h(r, g)$, the more the residents of r prefer the green space g. Altogether, we aim to find an assignment A such that the *total happiness* $\sum_{(r,g,i) \in A} h(r, g) \cdot i$ is maximized; we call that problem GreenSpaceAssignment. For any assignment A we assume that it only contains triples that contribute to the objective, i.e., there is no $(r, g, i) \in A$ such that $h(r, g) = 0$. We note that there might be residents that are not assigned to any green space; we say that these are *unsatisfied*, while all others are *satisfied*.

From a computational point of view, GreenSpaceAssignment can be easily reduced to finding a maximum flow in a complete bipartite graph formed by R and G; see Figure 1(a). For the convenience of the reader we present the corresponding LP formulation at this point. For each pair $(r, g) \in R \times G$ we introduce a variable $x_{r,g}$. We interpret $x_{r,g}$ as the number of residents of r assigned to g. Subject to

$$\sum_{g \in G} x_{r,g} \leq I(r) \text{ for all } r \in R \quad (1) \qquad \text{and} \qquad \sum_{r \in R} x_{r,g} \leq C(g) \text{ for all } g \in G \quad (2)$$

we maximize $\sum_{r \in R} \sum_{g \in G} x_{r,g} \cdot h(r,g)$. The assignment is $A = \{(r, g, x_{r,g}) \mid r \in R \wedge g \in G\}$.

In Section 3.3 we describe one possible variant of this highly general model in more detail in order to demonstrate its application. In Section 6 we sketch further variants.

3.3 Network-Based Assignment Model

We now introduce a specialization of our model in which green spaces are assessed by their attractiveness and their accessibility. We assume that residents prefer nearby and attractive green spaces and are not willing to use green spaces that are further away than a certain distance $d_{\max}$; we call this distance the *scope* of the residents. Further, we assume that the mobility of the residents may vary from residential area to residential area. To model the mobility of residents and the attractiveness of green spaces, we introduce for each residential area $r \in R$ and each green space $g \in G$ the weights α_r and β_g, respectively. A higher value corresponds with a higher mobility of the residents in r and a higher attractiveness of g, respectively. To assess the accessibility of a green space g from a residential area r, we take the distance $d(r,g)$ between r and g into account. We obtain this distance from the road network of the considered urban area. For a residential area r we then rate the green space g by $h(r,g) = \alpha_r + \beta_g - \frac{d(r,g)}{d_{\max}}$. We note that $h(r,g)$ may become negative. However, in this case no resident of r is assigned to g because we consider a maximization problem. Consequently, a negative value corresponds with setting $h(r,g) = 0$.

GreenSpaceAssignment can be solved using the LP formulation above. While this works out for small and medium sized cities, it easily exceeds the storage of a modern server system for large cities because it uses a quadratic number of variables. Instead, we introduce a specialized formulation based on the given road network. This formulation uses a number of variables that is linear in the number of green spaces, residential areas and the size of the road network. This allows us to consider metropolitan cities.

We assume that we are given the road network as a directed geometric graph $H = (V, E)$. From H we derive the *service network* $N = (V \cup R \cup G, E \cup F)$ by adding a vertex for each residential area and each green space; see Fig. 1(b). These vertices are connected to the remaining graph by means of the additional edges in F. More precisely, there is an edge $rv \in F$ with $r \in R$ and $v \in V$ if and only if v is an *access point* of the residential area r. Similarly, there is an edge $ug \in F$ with $g \in G$ and $u \in V$ if and only if u is an access point of the green space g. A vertex of the road network is an access point of a region if a resident may access the region via this point; in Section 4 we describe a simple tool to compute access points of residential areas and green spaces.

We set the length d of the edges in N as follows. For an edge $e \in E$ we define its length $d(e)$ as its geodesic length in the road network. For edges $rv \in F$ incident to a residential area r we define $d(rv) = \alpha_r$. Finally, for edges $ug \in F$ incident to a green space g we define $d(ug) = \beta_g$. Depending on the application we may define d differently, e.g., as travel time.

We are now ready to introduce our LP formulation for this specialized model. For each edge $e \in E \cup F$ we model a flow on e with a variable x_e. This represents the number of residents using edge e. We introduce the following linear constraints.

$$\sum_{rv \in F} x_{rv} \leq I(r) \qquad \text{for all residential areas } r \in R \tag{3}$$

$$\sum_{uv \in E \cup F} x_{uv} = \sum_{vw \in E \cup F} x_{vw} \qquad \text{for all road network vertices } v \in V \tag{4}$$

$$\sum_{ug \in F} x_{ug} \leq C(g) \qquad \text{for all green spaces } g \in G \tag{5}$$

Subject to these constraints we maximize the following objective

$$\sum_{r \in R} \sum_{rv \in F} \alpha_r \cdot x_{rv} + \sum_{g \in G} \sum_{ug \in F} \beta_g \cdot x_{ug} - \sum_{uv \in E} \frac{d(u,v)}{d_{\max}} \cdot x_{uv} \tag{6}$$

The first constraint states that for each residential area r the flow on the outgoing edges does not exceed the number of residents of r. The second constraint preserves the flow within the road network, i.e., flow entering a road network vertex $v \in V$ also needs to leave v on its outgoing edges. Finally, the last constraint ensures that the flow on the incoming edges of a green space does not exceed the capacity of the green space. Put differently, the number of residents that are assigned to a green space does not exceed the capacity of the green space.

The intuition behind the objective can be explained as follows. Consider the flow $z_{r,g}$ of a residential area r that is absorbed by a green space g. As the number of residents using the same edge in N is not limited, we can assume without loss of generality that the flow $z_{r,g}$ is not split anywhere in the flow network. Since each edge $uv \in E$ has cost $-\frac{d(u,v)}{d_{\max}}$ and since we consider a maximization problem, the flow from r uses a shortest path P in the road network to reach g; see Figure 1(c). Hence, the flow has value

$$\alpha_r \cdot z_{r,g} + \beta_g \cdot z_{r,g} - \sum_{uv \in P} \frac{d(u,v)}{d_{\max}} \cdot z_{r,g} = h(r,g) \cdot z_{r,g}. \tag{7}$$

Consequently, the value of the flow in total is $\sum_{r \in R} \sum_{g \in G} h(r,g) \cdot z_{r,g}$, which corresponds with the objective of GreenSpaceAssignment.

4 Deployment

We now describe the deployment of the network-based model (Section 3.3) in experiments and practical applications. This is just one way to apply our methodology, but it easily can be adapted to other scenarios. We assume that we are given the residential areas R and the green spaces G of an urban area as simple polygons. Each residential area has a number of residents. The road network is given as a graph $H = (V, E)$ with geometric embedding. We apply two phases. In the first phase, we preprocess the data in 5 steps obtaining an instance of GreenSpaceAssignment. In the second phase, we solve that instance.

First Phase – Preprocessing

Step 1. Since the polygons representing green spaces may be too large and complex to reasonably argue about the distances between them and polygons representing residential areas, it may be necessary to partition these polygons into smaller units. We use an approach by Haunert and Meulemans [11]. They decompose a simple polygon into a minimum number of simple polygons such that each of the resulting polygons is sufficiently compact, with respect to a measure of dilation from graph theory. We obtain a new set of green spaces formed by these compact polygons that replaces the green spaces in G.

Step 2. We determine the access points of the green spaces and the residential areas. To that end, we buffer each polygon; in our experiments we use an offset of 100 m. Hence, roads closely passing by the original polygon intersect the buffered polygon. Each vertex of the road network in the buffered polygon then is an *access point* of the original polygon.

Step 3. We construct the service network based on the road network H. We add the residential areas in R and green spaces in G as vertices to the road network. For each residential area $r \in R$ and each access point v of r, we introduce the edge rv. Similarly, we introduce for each green space $g \in G$ and each access point u of g the edge ug. We denote the set of edges incident to vertices representing residential areas and green spaces by F. Altogether, we obtain the service network $N = (V \cup R \cup G, E \cup F)$.

Step 4. To reduce the graph's complexity, we iteratively remove any degree-2 vertex by replacing its two edges with a single edge connecting its neighbors; the length of the new edge is derived from the two incident edges. Since we do not use the geometric embedding of H in the subsequent steps, this is a valid operation to speed up shortest path queries.

Step 5. In our model, we assume that residents only use shortest paths. Hence, for each vertex of the service network we compute whether it lies on a shortest path between a residential area and a green space. If this is not the case, we remove the vertex from the road network. Otherwise, we annotate the vertex with the smallest distance between it and any residential area; we call this distance the *accessibility* of the vertex. We use this distance in the second phase to prune the network.

Second Phase – Linear Programming

In this phase, we process the instance of GreenSpaceAssignment that we have created in the previous phase. To that end, we systematically explore different choices of capacities of green spaces as well as different scopes. More precisely, we assume that there is a demand γ of green space made by each resident; we call γ the *per-capita demand.* The capacity of a green space is then $\frac{\text{area of green space}}{\text{per-capita demand}}$. In our experiments, we not only consider one choice of γ but a set Γ of per-capita demands. Similarly, for the scope we consider a set D of distances. For each pair $(\gamma, d) \in \Gamma \times D$ we solve GreenSpaceAssignment on the respective instance. That is, we set the capacities of each green space g to $\frac{\text{area of } g}{\text{per-capita demand}}$. Applying $d_{\max} := d$, we then use the LP formulation to solve GreenSpaceAssignment on the corresponding instance. In the LP formulation, we only consider vertices whose accessibility does not exceed $d_{\max}$. As result we obtain for each pair (γ, d) the average distance between a resident's residential area and the assigned green space. Besides, for each residential area, we obtain the number of residents that were assigned to a green space. Analogously, for each green space, we obtain the number of residents assigned to this area.

Further, for each per-capita demand $\gamma \in \Gamma$ we compute the smallest scope $D_\gamma \in \mathbb{R}$ for which all residents are satisfied. We compute this distance using a simple parametric search.

5 Experiments

In this section, we describe our experimental evaluation that we use to assess our methodology. We emphasize that the aim of this evaluation is not primarily to find new insights into the structure of specific cities but to demonstrate that the methodology works in general and yields a manifold tool set to analyze the supply of green spaces.

5.1 Data and Experimental Setup

In our evaluation, we have considered 53 urban areas in Germany. As data basis, we use the Urban Atlas 2012[1]. For a selection of cities, this atlas provides detailed information about land use in the urban area. It particularly distinguishes between the city and its surroundings. For each city, we extract its residential areas as simple polygons excluding its surroundings. In this atlas, a residential area typically represents one housing block separated from others by roads. The data basis further provides for each residential area an estimated number of residents resulting from downscaling census data. Similarly, we extract green spaces as simple polygons for each city including its surroundings. In contrast to residential areas, green spaces may describe vast regions constituting large parts of the urban area. For our experiments, we only take green spaces tagged with *forest*, *green urban area*, or *sports and leisure facility*. Columns 1–3 of Figure 2 give an overview of the analyzed urban areas. The number of residents ranges from 33 thousand to 2.4 million; the cities have 285 thousand residents on average. The area of considered green spaces ranges from 8.6 km^2 to 6560 km^2; on average there are 659 km^2 of green space in the urban area. In addition, Column 3 yields information about the area of green space that is available per resident.

The road network is taken from OpenStreetMap[2]. We have chosen the extent of the road network such that any shortest path between residential areas and green spaces is included.

We configure the second phase of our approach as follows. To keep the evaluation simple, we choose $\alpha_r = 1$ for any residential area $r \in R$ and $\beta_g = 0$ for any green space $g \in G$. Hence, for any resident it yields the same gain to leave the according residential area, but there is no reward for entering specific green spaces. This particularly implies that any resident reaches any green space within the globally defined scope, but no resident may exceed that distance. In order to define the capacities and scopes as described in Section 4, we define the per-capita demands as $\Gamma = \{50 \cdot i \mid 1 \leq i \leq 20\} \cup \{1, 10\}$ in m^2 and the scopes as $D = \{0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 5, 6, 7, 8, 9, 10, 15, 20, 25, 30, 40, 50, 60, \infty\}$ in km. As described above, we solve GreenSpaceAssignment for all pairs $(\gamma, d) \in \Gamma \times D$. Further, for each $\gamma \in \Gamma$, we compute the smallest scope D_γ such that all residents are satisfied.

We solve the LP formulations using Gurobi 7.0.2[3]. For the LP formulations, we use continuous variables instead of integer variables. Hence, residents may be distributed on multiple areas. Since we are not interested in the specific assignment of a resident to a green space but aim to maximize the average happiness of the residents, this is a reasonable assumption improving the running time of the applied solver.

The experiments were performed on an Intel® Xeon® CPU E5-1620 processor. The machine is clocked at 3.6 GHz and has 32 GB RAM. The first phase of our approach is implemented in Python utilizing QGIS 2.18.14[4]. The second phase is written in Java.

5.2 Evaluation

In this section, we sketch different analysis techniques that can be used to assess the green-space supply of urban areas. To that end, we use the following measures.

- For each residential area its *largest satisfiable per-capita demand*: the largest per-capita demand $\gamma \in \Gamma$ such that every resident of that residential area is satisfied.

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[1] ©European Union, Copernicus Land Monitoring Service 2018, European Environment Agency (EEA). `http://www.land.copernicus.eu`

[2] `http://www.openstreetmap.org`

[3] `http://www.gurobi.com`

[4] `http://www.qgis.org`

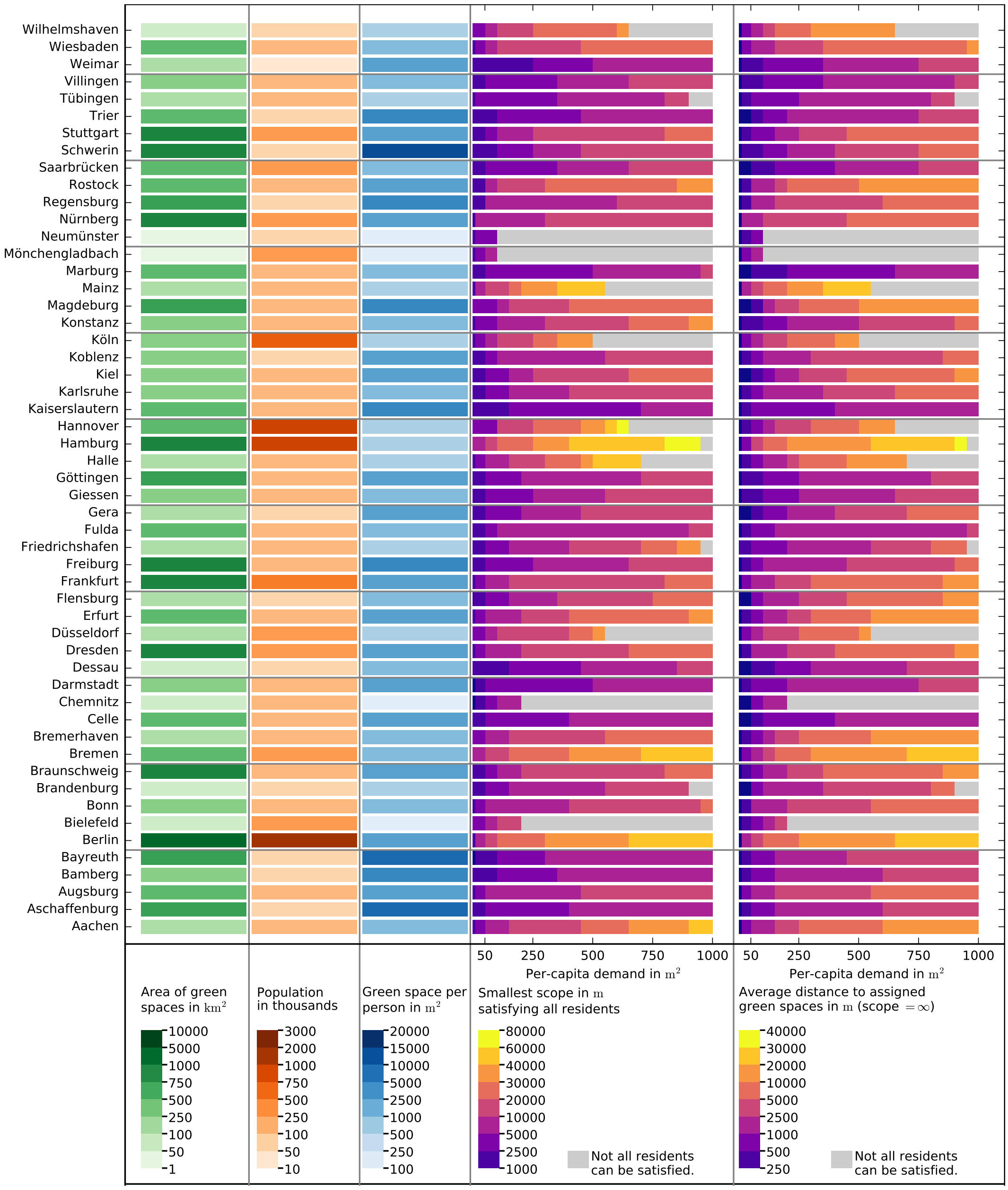
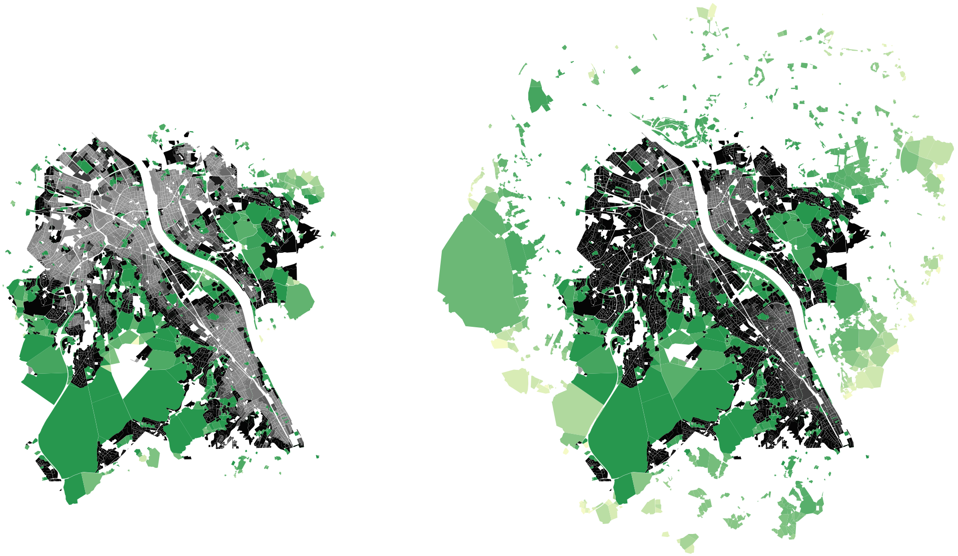


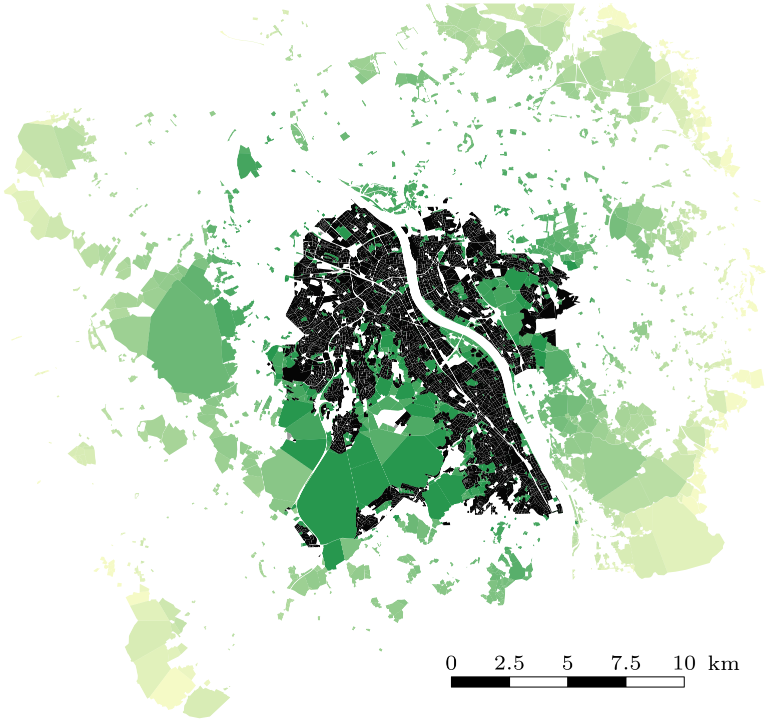
Figure 2 Results for 53 urban areas in Germany. The first three columns give some basic information about the urban areas while the two last columns summarize our results.

- For each green space its *smallest relevant per-capita demand*: the smallest per-capita demand $\gamma \in \Gamma$ such that the green space is used in the assignment.
- For each $\gamma \in \Gamma$ the *smallest scope satisfying all residents*: smallest scope such that all residents of all residential areas are satisfied.
- For each $\gamma \in \Gamma$ the *average distance to assigned green spaces*: the average distance to assign all residents to green spaces considering an infinitely large scope.



Scope 1500 m

Scope 8000 m



Scope 20 000 m

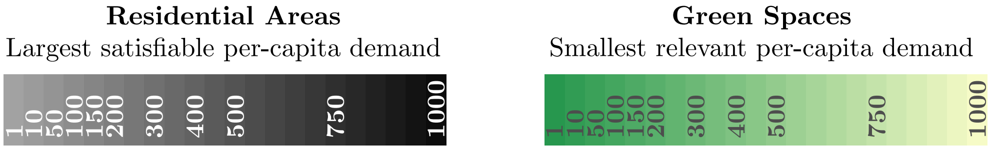


Figure 3 Green space supply of Bonn, Germany. An interactive illustration for every scope and every considered city is found on `http://www.geoinfo.uni-bonn.de/urbanarea`.

Green Space Supply of a Single Urban Area

In this section, we discuss the analysis of a single urban area. To that end, we exemplarily consider the urban area of the city of *Bonn*; see Figure 3. As a medium-sized city in Germany its extent can be printed using a reasonable resolution. Using a tool with the possibility of zooming into the map the analysis may also be done on larger cities.[5]

Figure 3 shows the urban area of Bonn with respect to the scopes 1500, 8000 and 20 000 in meters. For each scope we have drawn all residential areas as well as all the green spaces to which residents are assigned; all other green spaces are omitted. Consequently, with increasing scope, more green spaces are shown.

Furthermore, we color each green space with respect to its smallest relevant per-capita demand; see Figure 3. The higher the saturation of the color of a green space, the lower is the smallest relevant per-capita demand. Hence, the saturation of the color shows the *importance* of a specific green space. Similarly, we paint each residential area with respect to its largest satisfiable per-capita demand. The lighter the gray of the residential area is, the lower is the highest per-capita demand for which all residents can be satisfied. Hence, light grays indicate residential areas with poor access to green spaces while dark grays indicate residential areas with easy access to green spaces.

We observe that for the scope of 1500 m there are two regions in Bonn that have full access to green spaces only for small per-capita demands; see light gray regions in Figure 3. With increasing scope the green space supply is apparently improved because the residents begin to reach green spaces further away from the city. However, for the comparatively large scope of 8000 m, there are still residential areas that are only completely satisfied for small per-capita demands. We particularly note that our methodology is robust against small green spaces in the city center. They only impact some nearby residential areas, but do not influence the overall impression that the city center lacks green space supply. Further, the maps indicate that the green spaces on the south side of the city play a particularly important role as local recreation areas.

Comparing the Green Space Supply of Multiple Urban Areas

In our evaluation, we consider 53 cities of different size. Column 4 of Figure 2 shows the smallest scope that is sufficient to satisfy all residents of the considered urban area. The result of a specific urban area can be interpreted as the *robustness* of its green-space supply, which we motivate as follows. For 39 urban areas even a per-capita demand of $1000\,\mathrm{m}^2$ can be realized without leaving a resident unsatisfied. Hence, their green-space supply is hardly affected even for high per-capita demands. In contrast, there are 14 urban areas whose green-space supply collapses for smaller per-capita demands.

Considering the 39 urban areas in more detail, further differences of large extent are observable. There are 8 urban areas (e.g., *Aschaffenburg*, *Bamberg* and *Bayreuth*) whose scope does not exceed 10 km even if each resident requires $1000\,\mathrm{m}^2$. In contrast, for 16 of the 39 urban areas a scope of at least 20 km is necessary to satisfy all residents with per-capita demand of $1000\,\mathrm{m}^2$; with 48 km Berlin requires the largest scope among those cities.

Considering the 14 urban areas whose green-space supply collapses for per-capita demands smaller than $1000\,\mathrm{m}^2$, we observe that there are urban areas whose green-space supply already collapses for rather small per-capita demands up to $250\,\mathrm{m}^2$. For example, for *Neumünster* and

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[5] Illustrations for all considered scopes and cities are found at `http://www.geoinfo.uni-bonn.de/urbanarea`.

Mönchengladbach a per-capita demand of 150 m^2 is not realizable without leaving residents unsatisfied. In these cases, the small scopes indicate that the diameter of the considered surrounding area is not sufficient. In contrast, there are urban areas whose green-space supply collapses only for higher values. For *Hamburg*, for example, all residents can be satisfied up to a per-capita demand of 950 m^2. However, this requires a scope of 74 km. Hence, the robustness of its green-space supply is dearly bought by a large scope.

Column 5 of Figure 2 shows the average distance to assigned green spaces with respect to the per-capita demands; in case that not all residents can be satisfied the average distance is not presented. The result of a specific urban area can be interpreted as the *accessibility* of its green-space supply, which we motivate as follows. With increasing per-capita demand, the average distance increases depending on the green-space supply of the urban area. For cities with large nearby green spaces, the average distance increases more slowly than the average distance for cities with small nearby green spaces. Hence, for the latter, the local green-space supply becomes easily insufficient for satisfying all residents. For the urban area of *Marburg*, for example, the average distance to assigned green spaces increases slower than the average distance for the urban area of *Wiesbaden*. We emphasize that both regions have a similar population size and a similar total area of green space. Still, on average, the residents of *Marburg* need to cover smaller distances than the residents of *Wiesbaden*, which implies that the green spaces of *Marburg* are more easily accessible than the green spaces of *Wiesbaden*.

Running Time

A typical interactive scenario using our methodology could be as follows. The first phase is applied only once in order to create the service network at the very beginning of the scenario. Once the service network is created, its structure is not changed anymore, but the user gains the possibility of assigning to each residential area and green space attributes (e.g., number of residents, preferences, mobility, etc.). Instead of doing this only once, the user may repeatedly change the attributes to interactively explore the influence of single residential areas and green spaces. Each time, the second phase is executed. Hence, the performance of the repetitively executed second phase is clearly more crucial than the performance of the first phase. With this in mind, we have therefore focused on the second phase.

For the first phase, we put together standard algorithms without engineering their performance. For the urban area of *Berlin* (with 130 000 polygons representing green spaces, 18 000 polygons representing residential areas, and 6 million road segments our largest instance) the first phase takes about 3 minutes.

Solving the LP formulations used by far the greatest portion of the running time of the second phase. In our experiments, we measured the running time for solving $|C| \cdot |D| = 484$ LP formulations per region. Solving a single LP formulation, which we call a *run*, takes 46 seconds in maximum and 5 seconds on average. Over 95 % of all runs took at most 14 seconds. About 89 % of the runs took at most 10 seconds. These running times indicate that our approach does not allow real-time animations, but is usable in interactive systems where the user can update the assignment on demand. Apart from interactive systems, our approach can also be used for the systematic and automatic evaluation of green spaces. Accumulating the running times of all runs of a single urban area yields 3.3 hours in maximum and 40 seconds on average. In total, 35 hours were necessary to process for all 53 cities.

Summary

The presented evaluation demonstrates the strength of our methodology, which stands out by the following features.

- Detailed spatial analysis of single urban areas.
- Simultaneous evaluation of single residential areas and large regions with intuitive maps.
- Easy identification of local recreation areas.
- Robustness against small residential areas and green spaces.
- Sophisticated analysis of multiple urban areas with respect to different measures.
- Practical running times for interactive scenarios and the analysis of multiple urban areas.

We emphasize that domain experts from urban development confirmed the great use of this tool. They particularly highlighted the possibility of spatially analyzing single urban areas.

6 Conclusion & Outlook

We have presented a highly general model for the evaluation of green spaces of urban areas. It is based on the idea of assigning residents to green spaces maximizing the overall happiness of the residents while capacity constraints for green spaces are respected. We have described a specialization of the model and its deployment in detail. It utilizes the underlying road network for computing the assignment. The advantage of this specialization is the better performance obtained by the linear number of variables. This provides the possibility of considering metropolitan cities such as Berlin. In an exemplary evaluation, we demonstrated that the presented methodology can be used for analyzing a single urban area specifically as well as large sets of urban areas in general. Our approach not only yields abstract parameters describing the green-space supply, but it supports a spatial analysis based on the level of single residential areas and green spaces. A discussion panel with domain experts from urban development yielded that our approach will be of great use for urban planning to easily assess existing green-space supply as well as to plan future land usage. Especially, the methodology is of great use in interactive scenarios for urban planning. By means of our approach, an urban planner may interactively explore the influence of potential residential areas and green spaces using maps such as in Figure 3. They may change the importance of green spaces, the preference of residential areas, or even introduce new regions. Each time, our model is updated and the result is visualized. Thus, the user can easily assess the impact of the changes made.

In Section 3.3, we have described one specialization of the generic assignment model. However, the generality of our model provides many different variants. Among others, the following specializations and research questions arise.

- We kept our experiments simple to evaluate the core of our methodology. In practice, it lends itself to use a more complex parameterization reflecting reality more accurately like using travel times instead of geodesic distances in the road network. Further, one may differentiate the mobility of residents and the attractiveness of green spaces by adapting the weights α_r and β_g, respectively. Additionally, introducing further types of recreational areas such as lakes, rivers and open spaces promises a detailed evaluation.
- An interesting followup question is to analyze the utilization of the road network in detail. Which roads are used more than others? May these insights help in traffic planning, especially for weekends? A closer look at the computed flow may give insights.
- The network-based model anonymizes the assignment in the sense that we can not keep track of single residents, but we only obtain how many residents per residential area are assigned to specific green spaces. In some cases, however, it may be useful to analyze the exact assignment. In that case, one may use the generic model of Section 3.2.

- Our approach may also be used to evaluate the accessibility of public services. For example, the coverage of hospitals, medical practices, schools, playgrounds, etc., can be analyzed with our approach as well. In particular, depending on the accuracy of the given data, residential areas may be differentiated by their type of demands.

Altogether, we have presented a generic tool for the assessment of green spaces in urban areas. It can be easily adapted for different applications. For future work, we are planning to apply our methodology on concrete use cases in urban planning.

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