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Facility location problems in the plane based on reverse nearest neighbor queries

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ABSTRACT

For a finite set of points S, the (monochromatic) reverse nearest neighbor (RNN) rule associates with any query point q the subset of points in S that have q as its nearest neighbor. In the bichromatic reverse nearest neighbor (BRNN) rule, sets of red and blue points are given and any blue query is associated with the subset of red points that have it as its nearest blue neighbor. In this paper we introduce and study new optimization problems in the plane based on the bichromatic reverse nearest neighbor (BRNN) rule. We provide efficient algorithms to compute a new blue point under criteria such as: (1) the number of associated red points is maximum (MAXCOV criterion); (2) the maximum distance to the associated red points is minimum (MINMAX criterion); (3) the minimum distance to the associated red points is maximum (MAXMIN criterion). These problems arise in the competitive location area where competing facilities are established. Our solutions use techniques from computational geometry, such as the concept of depth of an arrangement of disks or upper envelope of surface patches in three dimensions.

1. Introduction

Given a database, a *nearest neighbor* (NN) query returns the data objects that are nearer to a given query object than any other object in the database. On the other hand, in the conceptually inverse query problem, a *Reverse nearest neighbor* (RNN) query retrieves those objects that have a query object as their nearest neighbor. Reverse nearest neighbors queries have emerged as an important class of queries for spatial and other types of databases. The concept was first introduced by Korn et al. [19,20]; the reader is referred to these papers for a gathering of a large number of applications in marketing and decision support systems. Also, see [30] for a survey on the current state-of-art and open geometric problems in another application area.

The RNN query itself presents several variants, ranging from monochromatic or bichromatic versions to static or dynamic versions. In the monochromatic case, all points have the same color. In the bichromatic case, the point set consists of red and blue points, and the problem turns into computing those points belonging to one of the two colors for which a query point is a bichromatic nearest neighbor. In the static version of the problem, distances between points in the set remain unchanged, whereas in the dynamic problem they may change. Some previous related work on these problems includes [6,22,23,27,29]. High-dimensional instances of RNN and BRNN (bichromatic RNN) have hardly been considered in the past, in sharp contrast with the NN problem; and it is striking to see how little research on (B)RNN has been carried out compared to the research on NN. This shows that even the planar instances of (B)RNN are still worth studying at the present time.

This paper considers the RNN query as a rule or mapping to associate points from the database to every point in a continuous space and introduces new optimization problems by using this rule. We study new geometric optimization problems in the planar static bichromatic variant, where data points belong to two categories. In particular, we will define *RNN facility location problems* in a two dimensional space. Some points are designated as facilities, and others as customers. In this setting, a *reverse nearest neighbor query* asks for the set of customers affected by the opening of a new facility at some point (query); here we will assume that all customers choose the nearest facility (Fig. 1). We point out here that we pick the name "reverse" from the data mining community and this concept is different from the "inverse" or "reverse" as used sometimes in the operational research field, where the goal is to modify the underlying space to improve the efficiency [33].

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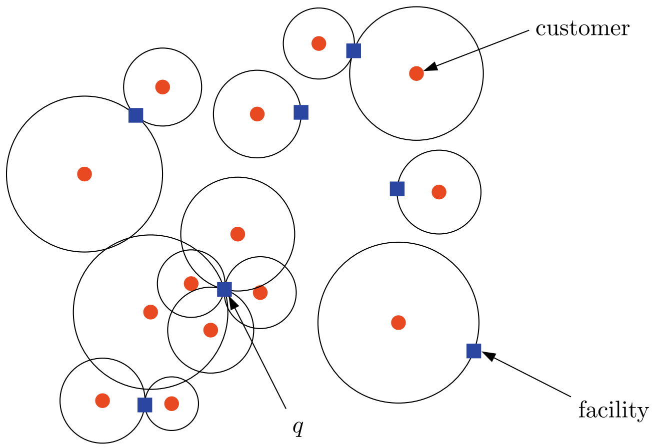

Fig. 1. The bichromatic RNN query. BRNN(q) has five points.

We will study optimization problems that arise when considering various optimization criteria: maximizing the number of potential customers for the new facility (MAXCOV criterion); minimizing the maximum distance to the associated clients (MINMAX criterion); and maximizing the minimum distance to the associated clients (MAXMIN criterion). The MAXCOV and MINMAX criteria deal with the location of an *attractive* facility (bars, discos, hospitals, schools, supermarkets, fixed wireless base stations, etc), while the MAXMIN criterion seeks the best location for a new *obnoxious* facility (rubbish dumps, chemical plants, etc.). Notice that these problems can be interpreted as the location of a new facility in a competitive environment. Competitive facility location addresses the problem of the placing of sites by competing market players. Typically, the expected income the new facility will generate will depend on the market share it will capture. Competitive location models have been studied in several disciplines such as geography, economics, marketing and operations research. Comprehensive surveys of competitive facility location models can be found in [14,15,24,31]. A continuous analogue to the MAXCOV problem was considered in [8,10], where the problem of placing a new facility in a location that maximizes the area of the corresponding Voronoi region is considered. Observe that the MAXCOV criterion can also be seen as a greedy step in a discrete version of the Voronoi game [2].

Finally, as already pointed out above, applications of the problems under consideration are also related to various fields that lie beyond the scope of facility location problems, for example, advanced database applications.

An outline of the paper is as follows: In Section 2 we state the optimization problems. In Section 3 we propose exact and approximate algorithms for the MAXCOV problem and we prove its 3SUM hardness. An $O(n^{2+\epsilon})$-time algorithm for the MINMAX and the MAXMIN problems is described in Section 4. In Section 5 we also consider several variants of the problems which include the combination of criteria, the use of the L_1 and L_∞-metrics and the reverse farthest neighbor version. Finally, concluding remarks of the paper are put forward in Section 6.

2. Problem statement

In the sequel, unless otherwise stated, we will use the L_2 metric and will $d(p,q)$ denote the Euclidean distance between points p and q. Let $S = \{p_1, \ldots, p_N\}$ be a set of points in the plane. Given a point b in the plane, the *reverse nearest neighbor set* of b is defined as

$$\mathrm{RNN}(b) = \{p_i \in S : d(p_i, b) \leqslant d(p_i, p_j),\ \forall p_j \in S \setminus \{p_i\}\}.$$

For the bichromatic case, assume we have a nonempty set $R = \{r_1, \ldots, r_n\}$ of n red points (clients) and a nonempty set $B = \{b_1, \ldots, b_m\}$ of m blue points (facilities) such that $n \geqslant m \geqslant 2$ and $R \cap B = \emptyset$. Given a new query blue point $b \notin B$, the *bichromatic reverse nearest neighbor set* is defined as

$$\mathrm{BRNN}(b) = \{r_i \in R : d(r_i, b) \leqslant d(r_i, b_j),\ \forall b_j \in B\}.$$

Notice that in the monochromatic case the size of the output of a query may differ from the size in the bichromatic case. The following result establishes such a difference.

Lemma 1 [28]. *For any query point, the set* RNN(b) *has at most six points, but the size of* BRNN(b) *may be arbitrarily large.*

It is straightforward to note that for any blue point $b \notin B$ we have $0 \leqslant |\mathrm{BRNN}(b)| \leqslant n$. Notice also that if $r_i \in \mathrm{BRNN}(b)$, then (by definition) the open disk centered at r_i and radius $d(r_i, b)$ is empty of blue points. We formalize the optimization problems as follows.

The MAXCOV problem. Given a bichromatic point set $S = R \cup B$, compute

$$\mathrm{MAXCOV}(S) = \max\{|\mathrm{BRNN}(b)| : b \in \mathbb{R}^2 \setminus B\},$$

that is, compute the maximum number of points that BRNN(b) contains for a point $b \notin B$, and find a witness placement b_0 such that $|\mathrm{BRNN}(b_0)| = \mathrm{MAXCOV}(S)$.

In the MAXCOV problem, we are also interested in computing the locus $\mathscr{L}_S$ of all points b satisfying $|\mathrm{BRNN}(b)| = \mathrm{MAXCOV}(S)$. More generally, for any positive integer k, we will consider computing the level set $L(k) = \{b \in \mathbb{R}^2 : |\mathrm{BRNN}(b)| \geqslant k\}$. Observe that $L(\mathrm{MAXCOV}(S)) = \mathscr{L}_S$ and $L(1) = \{b \in \mathbb{R}^2 : \mathrm{BRNN}(b) \neq \emptyset\}$.

The MINMAX problem. Given a bichromatic point set $S = R \cup B$ and a region $X \subseteq L(1)$, compute

$$\mathrm{MINMAX}(S) = \min_{b \in X} \max\{d(b,x) : x \in \mathrm{BRNN}(b)\},$$

and find a witness placement $b_0 \in X$ such that $\max\{d(b_0, x) : x \in \mathrm{BRNN}(b_0)\} = \mathrm{MINMAX}(S)$.

The MINMAX problem. Given a bichromatic point set $S = R \cup B$ and a region $X \subseteq L(1)$, compute

$$\mathrm{MAXMIN}(S) = \max_{b \in X} \min\{d(b,x) : x \in \mathrm{BRNN}(b)\},$$

and find a witness placement $b_0 \in X$ such that $\min\{d(b_0, x) : x \in \mathrm{BRNN}(b_0)\} = \mathrm{MAXMIN}(S)$.

For both MINMAX and MAXMIN problems we will add the additional constraint that the new point b has to be placed in a given region X with $X \subseteq L(1)$, as otherwise we could always place b such that $\mathrm{BRNN}(b) = \emptyset$. We will assume that X is a region bounded by $O(n)$ pieces, each with constant description complexity. The region X has to be bounded for the MAXMIN problem to be well-defined, and this condition is guaranteed by the fact that $X \subseteq L(1)$, which is always bounded. Typically, we will consider X to be a level set $L(k)$ for some value k. Although for some values k, the level set $L(k)$ can reach quadratic complexity in n, we will see that we will be able to handle this type of sets within the same asymptotic bounds.

Note that the MAXCOV and MAXMIN/MINMAX criteria are of completely different nature: while in the MAXCOV criterion our goal is to maximize the number of points in a set, which is a discrete measure, in the MAXMIN/MINMAX criteria we optimize a distance, which a is continuous measure. This difference in nature is reflected in the solutions that we present.

3. The MAXCOV problem

In this section we provide exact and approximate algorithms for the MAXCOV problem, as well as result on the hardness of the exact problem.

3.1. Exact solution

For every red point $r_i \in R$, we denote by $b(r_i)$ the nearest blue point. Let R_i be the *red disk* with radius $d(r_i, b(r_i))$ centered at point r_i. The set of n disks $\{R_1, \ldots, R_n\}$ can be computed in $O((n+m)\log m) = O(n \log m)$ time as follows: compute the Voronoi diagram of B and preprocess it for point location; after $O(m \log m)$ time, a point location query can be answered in $O(\log m)$ time [5]. By locating each $r_i \in R$ in the Voronoi diagram, we obtain points $b(r_1), \ldots, b(r_n)$ in $O(n \log m)$, which is information sufficient to construct the set of disks $\{R_1, \ldots, R_n\}$.

Let $\mathscr{A}$ be the arrangement generated by the set of n red disks $\{R_1, \ldots, R_n\}$. The idea of the algorithm is to associate a label l_c to each cell c of $\mathscr{A}$. Such label l_c will contain the number of discs that makes up the cell c. Next, the algorithm will look for the cells in $\mathscr{A}$ with maximum label. Indeed, if a cell c has label k, it means that a blue point b inside this cell c is contained in exactly k red disks; this means that the point b is the closest point of the k red points corresponding to the red disks. Observe that if we do not assume general position, the cell with greatest label may be a vertex of $\mathscr{A}$, such as the vertex b in Fig. 2.

The arrangement $\mathscr{A}$ along with the labels l_c for each cell $c \in \mathscr{A}$ can be constructed in $O(n^2 \log n)$ time using a standard sweep-line algorithm such as that of Bentley and Ottmann [7]. Computing the arrangement determined by a set of curve segments in the plane is a classical problem in computational geometry. A slightly faster construction of the arrangement $\mathscr{A}$ with $O(n^2)$ expected running time is proposed in [12,26]. More recently, a deterministic algorithm that use a divide-and-conquer approach to achieve an optimal running time $O(n^2)$ has been described in [3].

As we are dealing with the planar case, the computation of an arrangement of circles is of acceptable complexity. Utilizing an arrangement of circles is reminiscent of the approach of [19], where the RNN problem is reduced to point location among balls.

Once we have computed the arrangement $\mathscr{A}$ induced by the disks $\{R_1, \ldots, R_n\}$, we can construct the dual graph G of the arrangement. G will contain a node for each cell $c \in \mathscr{A}$ and an edge between two cells whenever their closures intersect. If two faces $c, c' \in \mathscr{A}$ are adjacent in G, it is easy to compute the label $l_{c'}$ from the label l_c. Therefore, making a traversal in the dual graph G, we can compute the labels l_c for all faces $c \in \mathscr{A}$. With this information, it is possible to compute l_c for all the edges and vertices $c \in \mathscr{A}$. Special care has to be paid when the arrangement is degenerate, that is, if some disks in $\{R_1, \ldots, R_n\}$ are tangent; details are standard and will be therefore omitted. After computing l_c for all cells $c \in \mathscr{A}$, we can find MAXCOV(S) using that MAXCOV$(S) = \max\{l_c | c \in \mathscr{A}\}$ and report the locus $\mathscr{L}_S$ of all optimal placement using that $\mathscr{L}_S = \bigcup_{\{c \in \mathscr{A} : l_c = \text{MAXCOV}(S)\}} c$. We end this discussion by stating the following theorem.

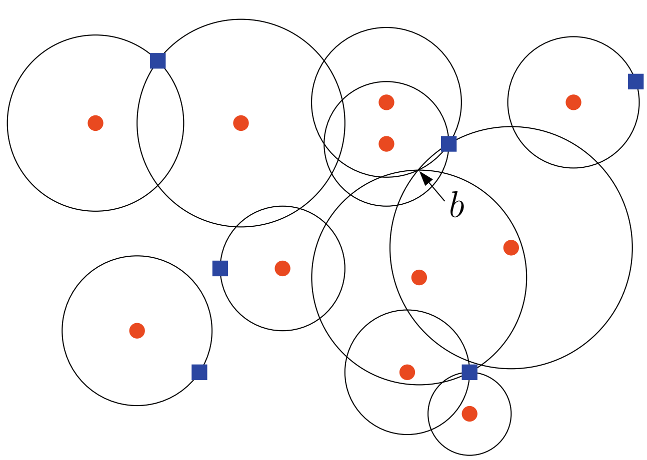

Fig. 2. Arrangement of red circles $R_1, \ldots, R_n$. (For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.)

Theorem 1. *The value* MAXCOV(S) *and the set of all optimal placements* $\mathscr{L}_S$ *can be computed in* $O(n^2)$ *worst-case running time.*

We can also construct any of the level sets $L(k)$ in the same running time. However, observe that the level set $L(1)$ is exactly the union of the n disks $R_1, \ldots, R_n$ and can be described in linear space and constructed in near-linear time [18]. Once we obtain a level set $L(k)$ under the MAXCOV criterion, we can compute the level that optimizes MAXMIN or MINMAX criteria. We will show how to deal with this in Section 5.1.

3.2. Approximation algorithm

In the preceding we gave a quadratic running-time algorithm for solving the MAXCOV problem. Below we will show that solving the MAXCOV problem is actually 3SUM hard [16]. This implies that a sub-quadratic algorithm is unlikely to exist. In some applications, however, it may be the case that a quadratic time algorithm is not affordable. We will then content ourselves with an approximation algorithm that places a new suboptimal facility. The number of clients this suboptimal facility will acquire may be smaller than that of the optimal placement, but the running time of the algorithm will in turn be close to linear.

As established above, computing MAXCOV(S) is equivalent to finding the *maximum depth* in the arrangement of disks $\mathscr{A}$. In other words, computing MAXCOV(S) can be reduced to finding a point in the plane having the largest number of covering disks . It also stems from the previous discussion that, if we find a point b whose depth in $\mathscr{A}$ is d, then it can be concluded that $|\text{BRNN}(b)| = d$, and so MAXCOV$(S) \geqslant d$. A probabilistic algorithm to compute a point that $(1-\varepsilon)$-approximates the maximum depth in an arrangement of n disks is given by Aronov and Har-Peled [4], and it readily leads to the following result.

Theorem 2. *Given a parameter* $\varepsilon > 0$, *we can find in* $O(n\varepsilon^{-2} \log n)$ *expected time a placement that, with high probability, is a* $(1-\varepsilon)$*-approximation to* MAXCOV(S).

Proof. In Section 3.1 we showed how to compute the set of n red disks $\{R_1, \ldots, R_n\}$ in $O(n \log m)$ time. Hence, by using the probabilistic algorithm of Aronov and Har-Peled [4] we can approximate the maximum depth in a family of pseudo-disks. $\square$

3.3. Complexity of MAXCOV

The hardness of the problem changes substantially from $m = 1$ to $m = 2$. We will show below that for $m = 2$ the problem is 3SUM hard [16], and therefore is at least as hard as many other problems for which no sub-quadratic algorithm is yet known. On the other hand, for $m = 1$, the problem can be solved in $O(n \log n)$ time, and this is asymptotically optimal in the algebraic decision tree model of computation (see Theorem 4).

Theorem 3. *For* $m \geqslant 2$, *computing* MAXCOV(S) *is 3SUM hard.*

Proof. The present proof is similar to the one used in [4] for showing the 3SUM hardness of computing the maximum depth in an arrangement of disks. In this paper, the authors used a well-known 3SUM hard problem in the reduction: given a set of lines in the plane with integer coefficients, decide whether any three of the lines have a point in common [16]. We show how to reduce this problem to the problem of computing MAXCOV(S). In contrast to that problem, where the input is a collection of disks, here we have to reduce our problem to an instance of MAXCOV, whose input is a set of red and blue points. Since not all collections of disks can arise from a MAXCOV problem, and furthermore since we want a set of 2 blue points, the original reduction does not apply directly.

Let L be a set of n lines with integer coefficients and distinct slopes. See Fig. 3 for the following construction. We first find an axis-parallel rectangle Q enclosing all the vertices of the arrangement of lines $\mathscr{A}(L)$. A rectangle Q can be computed in $O(n \log n)$ time by noting that the leftmost, rightmost, topmost, and bottommost intersection points are defined by lines with (circularly) consecutive slopes.

Let d be the diameter of Q and q the center of Q. Because the coefficients of the lines are integers, we can compute in linear time a value Δ such that all lines not incident to a vertex of $\mathscr{A}(L)$ are at a distance at least Δ from that vertex.

Let us assume that q lies at $(0,0)$, and consider the points $b^+ = (0,\beta), b^- = (0,-\beta)$ for some value β to be fixed shortly. We then represent each line $\ell \in L$ by using two red points according to the following construction: let p_ℓ and p'_ℓ be the intersection points between ℓ and the boundary of Q, let D^+_ℓ and D^-_ℓ be the respective disks with boundary through b^+, p_ℓ, p'_ℓ and b^-, p_ℓ, p'_ℓ, and let r^+_ℓ and r^-_ℓ be the respective centers of D^+_ℓ and D^-_ℓ. We can assume that the radii of the disks are large enough compared to the dimensions of Q in order to make sure that the bounding circles of these two disks intersect the boundary of Q in only two points, namely p_ℓ and p'_ℓ. Let $B = \{b^+, b^-\}$, let R be the set of $2n$ red points $\{r^+_\ell, r^-_\ell | \ell \in L\}$, and let $S = R \cup B$.

For each line $\ell \in L$, point r^+_ℓ is above the x-axis, while r^-_ℓ is below the x-axis. Therefore, b^+ is the blue point closest to r^+_ℓ and b^- is the blue point closest to r^-_ℓ.

It is possible to choose β sufficient large, so that $D^+_\ell \cap D^-_\ell$ is contained in a strip of width Δ around ℓ. This ensures that a vertex of the arrangement $\mathscr{A}(L)$ is contained in $D^+_\ell \cap D^-_\ell$ if and only if it is incident to ℓ. Elementary trigonometry shows that $\beta = \Delta + \Delta^{-1} \cdot d$ is large enough, and therefore the construction only uses numbers polynomially bounded.

A new blue point b will capture a red point r^+_ℓ (or r^-_ℓ) if and only if it is contained in D^+_ℓ (or D^-_ℓ, respectively). Every point inside of Q is contained either in D^+_ℓ or D^-_ℓ for every ℓ, and so every point in Q is contained in at least n disks, and no point outside of Q is contained in more than n disks. Furthermore there is a point in Q contained in at least $n+3$ disks (i.e., point $b \in Q$ is a witness such that $\mathrm{MAXCOV}(S) \geqslant n+3$) if and only if three lines of L intersect in a common point. The overall reduction takes $O(n \log n)$ time. $\square$

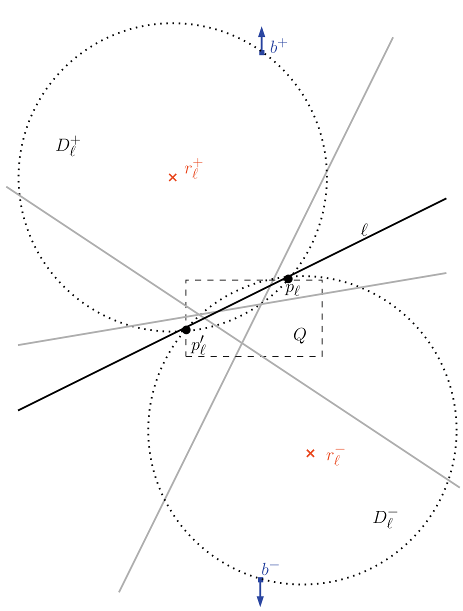

Fig. 3. Construction in the 3SUM hardness proof.

Theorem 4. *The value* MAXCOV(S) *for a set S of n red points and one blue point can be computed in $O(n \log n)$ time, and this is asymptotically optimal under the algebraic decision tree model.*

Proof. Let b be the only blue point and assume that there are not three points on a line. We find an open half-plane H_b with b on its boundary that contains as many red points as possible. This can be done in $O(n \log n)$ time by sorting the red points radially from b and performing a rotational sweep of a half-plane with b on its boundary. We then place a new blue point b' close enough to b such that b' captures all the points in $R \cap H_b$. It is obvious that this is an optimal solution, and we have found it in $O(n \log n)$ time.

Next we prove a lower bound. From the discussion in Section 3.1, it is clear that it is sufficient to show an $\Omega(n \log n)$ lower bound for the problem of finding the depth of an arrangement of n disks passing through a common point. Consider the *uniform gap* problem in a quadrant of the unit circle: Given n points $\{p_1, \ldots, p_n\}$ in a quadrant of the unit circle $\mathbb{S}^1 = \{(x,y) \in \mathbb{R}^2 \mid x^2 + y^2 = 1\}$, and a value $\varepsilon > 0$, decide whether there is a permutation $\sigma : \{1, \ldots, n\} \to \{1, \ldots, n\}$ such that $d(p_{\sigma(i)}, p_{\sigma(i+1)}) = \varepsilon$ for all $i \in \{1, \ldots, n-1\}$, where the distance $d(\cdot,\cdot)$ refers to the Euclidean distance. This problem has a lower bound of $\Omega(n \log n)$ time in the algebraic decision tree model [21,25].

Given an instance $P = \{p_1, \ldots, p_n\}, \varepsilon$ for the uniform gap problem, we make the following reduction to our problem; see Fig. 4. For each i, let q_i, q'_i be the points on $\mathbb{S}^1$ at distance ε from p_i, let ℓ_i, ℓ'_i be the lines bisecting segments $\overline{p_i q_i}$ and $\overline{p_i q'_i}$, and let D_i and D'_i be the disks that have o, p_i on their boundary and are tangent to ℓ_i and ℓ'_i, respectively. Note that $D_i \cap D'_i$ lies in one of the wedges defined by ℓ_i and ℓ'_i.

Let o be the blue point, and let the centers of the disks D_i be the set of $2n$ red points for our instance of the MAXCOV(S) problem. Let $\mathscr{D}$ be the set of $2n$ disks $\{D_i, D'_i | p_i \in P\}$. The set $\mathscr{D}$ can be constructed in linear time; we next show how to compute the depth of the arrangement $\mathscr{D}$ gives the answer to the uniform gap problem. If the answer to the instance P, ε is *yes*, then all the regions $D_1 \cap D'_1 \setminus \{o\}, \ldots, D_n \cap D'_n \setminus \{o\}$ are disjoint, and the maximum depth of $\mathscr{D}$ is $n+1$ (the point o has depth $2n$, but since o is a blue point, we cannot place another blue point there). On the other hand, if there are indices i,j such that $d(p_i, p_j) < \varepsilon$, then

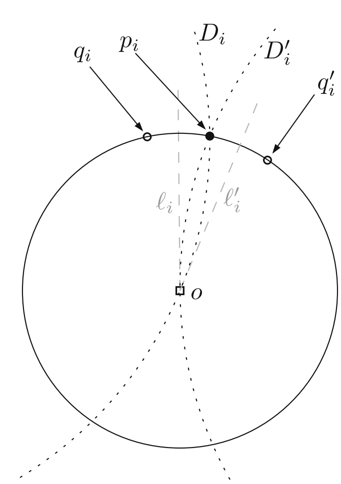

Fig. 4. Reduction in Theorem 4.

$D_i \cap D_i' \cap D_j \cap D_j' \setminus \{o\} \neq \emptyset$, and therefore the depth of the arrangement is, at least, $n+2$. Finally, we are left with the case when the answer to the gap problem is *no* because in all permutations a pair of consecutive points are at distance larger than ε. This case can be ruled out from the beginning by finding the leftmost and the rightmost points in P (which are well defined because P is in one quadrant) and checking that they are at the appropriate distance. □

4. The MINMAX and MAXMIN problems

We are given a bichromatic set $S = B \cup R$ formed by a set of m blue points B (facilities) and a set of n red points R (clients), $n \geqslant m \geqslant 2$, and a constraint region $X \subseteq L(1)$.

4.1. The MINMAX problem

According to the MINMAX criterion we are interested in finding a new blue point $p \in X$ such that the maximum distance to the points in BRNN(p) is minimized. Consider the cost function $Cost : L(1) \to \mathbb{R}$ that measures for each point $p \in L(1)$ the cost, according to the MINMAX criterion, of placing the new blue point, or facility, at p; it follows that $Cost(p) = \max\{d(p,x) : x \in BRNN(p)\}$. Consider the graph of the function *Cost* in 3*D*. Next, we are going to give a combinatorial description of this graph.

Embed the plane containing R, B in the plane $z = 0$ in 3-space, that is, consider the point sets R, B as embedded in the xy-plane in 3D. For a "client" point $r_i = (x_i, y_i) \in R$, consider the (solid) cylinder

$$Cyl_i = \{(x,y,z) \in \mathbb{R}^3 | (x-x_i)^2 + (y-y_i)^2 \leqslant (d(r_i, b(r_i)))^2\},$$

which is the vertical, solid cylinder through the disk centered at r_i with radius $d(r_i, b(r_i))$, and consider the (surface) cone

$$Con_i = \{(x,y,z) \in \mathbb{R}^3 | (x-x_i)^2 + (y-y_i)^2 = z^2,\ z \geqslant 0\}$$

with apex at point $(x_i, y_i, 0) \in R$. See Fig. 5 left for an example. Finally, let Σ_i be the portion of the surface Con_i contained in Cyl_i. Observe that Σ_i is a surface patch with constant complexity. See Fig. 5 right for an example.

The reason for considering Σ_i for each point r_i is the following: $\rho = (x,y,t) \in \mathbb{R}^3$ is a point vertically above (resp. below) Σ_i if and only if $r_i \in BRNN(x,y)$ and $d((x,y), r_i) \leqslant t$ (resp. $d((x,y), r_i) \geqslant t$). To see the validity of this claim, observe that ρ has a vertical above/below relation with Σ_i if and only if $\rho \in Cyl_i$. Moreover, by the way the cone Con_i is defined, it holds that $\rho = (x,y,t)$ is above Con_i if and only if $d((x,y), r_i) \leqslant t$. A similar analysis applies to a point ρ below Σ_i and the claim follows.

Let U be the upper envelope of the surfaces $\Sigma_1, \ldots, \Sigma_n$. Using the discussion above we readily obtain the following property.

Lemma 2. *The upper envelope U is the graph of the function Cost.*

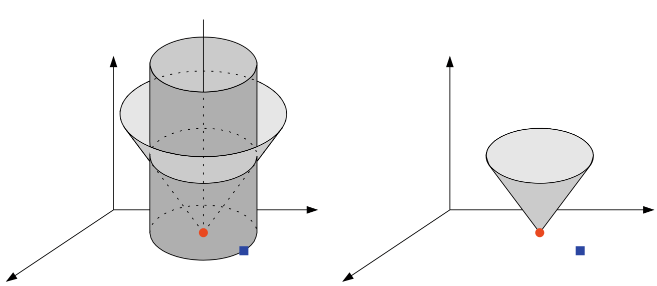

Fig. 5. Left: solid cylinder Cyl_i and cone Con_i associated to the point $r_i \in R$. Right: surface patch Σ_i associated with $r_i \in R$.

We are interested in finding a point $p \in X$ that minimizes *Cost*, and therefore the problem is reduced to finding the lowest point in the envelope U restricted to the region X. Let U_X be the portion of U defined over X. If X has complexity $O(n)$ we can argue that U_X has complexity $O(n^{2+\varepsilon})$ as follows, where the complexity of an envelope U_X is defined as its number of vertices, edges, and faces. For each boundary arc $a \in X$, we consider a vertical wall $W_a = a \times \mathbb{R}$ in 3D. Since X has $O(n)$ complexity, we have $O(n)$ surfaces of the type W_a.

The upper envelope U_W of the surfaces $\Sigma_1, \ldots, \Sigma_n$ together with the walls W_a for arcs a in the boundary of X can be computed and described in $O(n^{2+\varepsilon})$ time, for any fixed $\varepsilon > 0$ [1]. However, since we have introduced the vertical walls W_a, the domain of each patch of U_W is either fully contained in X or fully outside X. It follows that the restriction U_X of U to X can be constructed in $O(n^{2+\varepsilon})$ time.

It remains to find the lower point of U_X. Observe that this point does not necessarily have to be a vertex. However, finding the lower point of U_X can be done by checking each component of U_X, that is, each vertex, edge, and face. For a vertex and an edge in U_X, the lower point can be found in constant time, while for each face in U_X we can find the minimum in time proportional to its complexity. Since the complexity of U_X is $O(n^{2+\varepsilon})$, we conclude the following.

Theorem 5. *The MINMAX problem can be solved in $O(n^{2+\varepsilon})$ time, for any fixed $\varepsilon > 0$.*

4.2. The MAXMIN problem

Using the same approach, the MAXMIN problem can be solved by computing the lower envelope L of $\Sigma_1, \ldots, \Sigma_n$, considering its restriction L_X to a given set X, and finding the highest point in L_X. The same analysis applies to this case, and we obtain the following result.

Theorem 6. *The MAXMIN problem can be solved in $O(n^{2+\varepsilon})$ time, for any fixed $\varepsilon > 0$.*

5. Extensions

In this section we consider some extensions of the problems above. First, we combine the MINMAX or MAXMIN criteria with the MAXCOV criteria. Second, we solve the same problems as above under the L_1 and L_∞-metrics. Finally, we consider a different rule to associate clients to facilities, namely, the furthest neighbor rule.

5.1. MINMAX and MAXMIN criteria for optimal MAXCOV solutions

In Subsection 3.1 we have shown that the locus $L(k)$ of all placements achieving k clients can be found in near-quadratic time. Here we describe how to find the best location b within $L(k)$ according to the MINMAX criterion. The MAXMIN criterion can be handled similarly.

Theorem 7. *According to the MINMAX criterion, the best location in the set of placements in a level set $L(k)$ can be computed in $O(n^{2+\varepsilon})$ time, for any fixed $\varepsilon > 0$.*

Proof. We use a combination of ideas from Subsection 3.1 and Section 4. Like in Section 4, let U be the upper envelope of the surface patches $\Sigma_1, \ldots, \Sigma_n$. We are interested in finding the lower point of U restricted to the locus $L(k)$, for some value k. Recall that for each point r_i the circle R_i is centered at r_i and has radius $d(r_i, b(r_i))$. Observe that each cell of $L(k)$ is a cell in the arrangement $\mathscr{A}$ of disks $R_1, \ldots, R_n$. Let U_k be the restriction of the upper envelope U to the set $L(k)$. We next argue that U_k has complexity $O(n^{2+\varepsilon})$ and can be constructed in $O(n^{2+\varepsilon})$ time. For each disk R_i, consider the (surface) cylinder $C_i = R_i \times \mathbb{R}$ in $\mathbb{R}^3$. The upper envelope U' of the surfaces $\Sigma_1, \ldots, \Sigma_n, C_1, \ldots, C_n$ has complexity $O(n^{2+\varepsilon})$ and can be constructed in $O(n^{2+\varepsilon})$ time [1]. Moreover, because we have included $C_1, \ldots, C_n$ in the set of surfaces, the domain of each patch of U' is contained in a cell in the arrangement $\mathscr{A}$. In particular, the restriction of U_k to a cell of $c \in L(k)$ is the same as the restriction of U' to the same cell. We conclude that the envelope U_k has complexity $O(n^{2+\varepsilon})$, and we can find the lower point in U_k using $O(n^{2+\varepsilon})$ time by checking each component of U_k independently. □

Clearly, by finding the highest point of the corresponding lower envelope, similar result applies if we replace the MINMAX criterion by the MAXMIN criterion. Details are omitted.

5.2. The problems under the L_1 and L_∞-metrics

The distance function between facilities and clients depends on the kind of applications. Euclidean distance is appropriate when facilities and clients are spatially located. However, it is also common in location theory to use other distances [11]. In the following, we show how to apply the same techniques for the problems under the L_1 and L_∞ metrics.

Consider the L_∞ metric. For the MAXCOV criterion, the ideas described in Subsection 3.1 directly apply, but they yield better running times. As above, let R_i be the disk (square) with radius $d_\infty(r_i, b(r_i))$ centered at point r_i, and define the arrangement $\mathscr{A}$ induced by $\{R_1, \ldots, R_n\}$. We have to compute the maximum depth of $\mathscr{A}$. Although $\mathscr{A}$ may have quadratic complexity, the maximum depth in an arrangement of n rectangles can be found in $O(n \log n)$ time. This corresponds to a maximum clique in the intersection graph of rectangles [17].

Alternatively, we may use a sweep-line algorithm maintaining a segment tree describing the depth of the line in the arrangement [9]. Since the same argument applies to the L_1 metric, this leads to the following result.

Theorem 8. *In the L_∞ and L_1 metrics, we can compute MAXCOV(S) and a witness placement in $O(n \log n)$ worst-case running time.*

Observe that the description of all the optimal placements may take $\Omega(n^2)$, since it may consist of the union of many cells from $\mathscr{A}$. Of course, the 3SUM-hardness proof does not carry to the L_∞ or L_1 metric, and there is no need to consider approximation algorithms.

Theorem 9. *In the L_∞ and L_1 metrics, the MINMAX problem can be solved in $O(n^2\alpha(n))$ time.*

Proof. For the MINMAX criterion, the same ideas as described for the L_2 metric apply. For each point r_i, we consider the square cylinders $Cyl_i = R_i \times \mathbb{R}$, and the polyhedral cones Con_i such that its section at $z = t$ corresponds a square centered at r_i and side length $2t$. Notice that Σ_i is a surface consisting of 4 triangles, that is, 4 piece-wise linear patches. As above, we want to compute the upper envelope of these linear patches, which can be done in $O(n^2\alpha(n))$ time [13]. The rest of the analysis carries out like before, and we obtain the following improved bound. □

5.3. The reverse farthest neighbor problem

In above Sections we considered the notion of "influence" of a data point on a database as introduced in [19]. In many decision support situations the notion of the "influence set" of a data point is given in terms of geographical proximity or similarity and the distance between vectors is taken as a measure of dissimilarity. If we base the influence set on dissimilarity rather than similarity, the farthest neighbor rather than nearest neighbor can be considered. In [19,30], finding the set of all reverse farthest neighbors for a query point under the L_2 distance has been proposed as open problem in the monochromatic version. We study here the bichromatic version for the MAXCOV optimization problem. We define the influence set of a blue point b to be the set of all red points r such that b is further from r with respect to any other blue point. More formally, the *bichromatic reverse farthest neighbor set* is defined as

$$\mathrm{BRFN}(b) = \{r_i \in R : d(r_i, b) \geqslant d(r_i, b_j), \forall b_j \in B\}.$$

We would like to locate a new obnoxious facility and, in order to minimize the risk of this location, maximize the number of clients far away from the new undesirable facility. In this case, a suitable criterion is the MAXCOV as above, but using the farthest neighbor rule. To the best of our knowledge, this problem has not been studied in the literature before this paper. It is worth mentioning that in a recent paper [32], the problem has been examined from a practical point of view and many interesting applications in spatial databases are given. We formalize the new optimization problem as follows.

farthest MAXCOV problem. Given a bichromatic point set $S = R \cup B$ and a region $X \subset \mathbb{R}^2$, compute $\mathrm{MAXCOV}(S) = \max\{|\mathrm{BRFN}(b)| : b \in X \setminus B\}$, that is, compute the maximum number of points that $\mathrm{BRFN}(b)$ may have for a new point $b \in X \setminus B$, and find a witness placement $b_0 \in X \setminus B$ such that $|\mathrm{BRFN}(b_0)| = \mathrm{MAXCOV}(S)$.

Notice now that for this problem we also consider the additional constraint that the new point b has to be placed in a given, *bounded* region X, as otherwise, we could always place b to the infinity and the problem is trivially solved. See Fig. 6 for an example.

An algorithm similar to the one of Section 3.1 can be applied. For every red point $r_i \in R$, we denote by $b(r_i)$ a *farthest* blue point. Let R_i be the *red disk* with radius $d(r_i, b(r_i))$ centered at point r_i. The set of n disks $\{R_1, \ldots, R_n\}$ can be computed in $O(n \log m) = O(n \log n)$ by using the *farthest* Voronoi diagram of B and preprocessing it for point location [5]. The main observation now is that for any query b, the reverse farthest neighbors r_i are those for which the circles R_i do *not* include b. Therefore, given the arrangement $\mathscr{A}_F$ produced by the set of n red disks $\{R_1, \ldots, R_n\}$, the problem reduces to compute, for each cell $c \in \mathscr{A}_F$, the number of red circles that do not contain the cell c. This value can be obtained observing that, if a cell c has depth k, then we can attach to c the label $l_c = n - k$. In this way, we obtain the solution in $O(n^2)$ worst-case running time.

However, the following result shows that we only need to search for an optimal solution in the boundary of X.

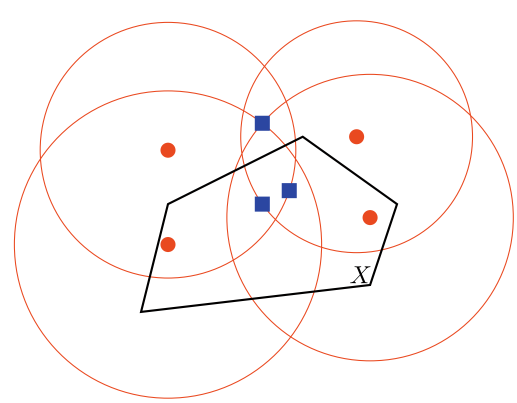

Fig. 6. Arrangement $\mathscr{A}_F$ and the constraint region X.

Lemma 3. *If the constraint region X is bounded, there exists a witness point b_0 on the boundary of X that attains $|BRFN(b_0)| = MAXCOV(S)$.*

Proof. Note that all the blue points B are contained in each of the disks R_i by the definition of the disks $R_1, \ldots, R_n$ are defined. Therefore, all the disks $R_1, \ldots, R_n$ have a common intersection that contains B. Let p_R be any point in $R_1 \cap \cdots \cap R_n$.

Let c be a cell of $\mathscr{A}_F \cap X$ that has minimum depth, among the cells of $\mathscr{A}_F \cap X$. We claim that c intersects the boundary of X, which proves the statement. Indeed, consider a point $p_c \in c \subseteq X$, and consider a straight walk from p_c in the direction of the vector $\overrightarrow{p_R p_c}$. Because $p_R \in R_1 \cap \cdots \cap R_n$, the ray from p_R to p_c can only exit disks and the depth can only decrease during this walk. Hence the minimum depth is attained when the walk reaches the boundary of X. $\square$

As mentioned before, if X is unbounded, the problem can be trivially solved. When X is bounded, Lemma 3 implies that the search can be restricted to the boundary ∂X of X, which is a one-dimensional space. If the boundary of X has a constant description complexity, the region $\partial X \cap R_i$ has $O(1)$ connected components, for any disk R_i. In this case, we can easily construct the restriction of $\mathscr{A}_F$ to ∂X in $O(n \log n)$ time. Finally, note that we did not explicitly use the L_2 metric, and therefore, the approach also works for the L_∞ and L_1 metrics. We summarize.

Theorem 10. *Let $X \subset \mathbb{R}^2$ be a region with constant description complexity. In the L_1, L_2, and L_∞ metrics, one can solve in $O(n \log n)$ time the furthest MAXCOV problem in the constraint region X for a set of n red points and m blue points, $m \leqslant n$.*

6. Concluding remarks

Given a query blue point, the bichromatic reverse nearest neighbor problem is to find all red points for which the query point is a nearest blue neighbor under some given distance metric. Such queries repeatedly arise when designing efficient algorithms in a variety of areas. In this paper, we introduced and efficiently solved some optimization problems with a direct interpretation in the area of Competitive Facility Location. In particular, we studied three problems (MAXCOV, MINMAX, and MAXMIN) for L_2, L_1 and L_∞ metrics.

The facility location problems usually consider weights measuring the importance of the sites (clients). The MAXCOV problem can be solved analogously in the weighted case. We may also consider to have multiplicative weights for the MINMAX problem, i.e., each point r_i gets a weight w_i and we want to minimize the maximum $w_i d(r_i, b)$ where $r_i \in \mathrm{BRNN}(b)$. In this case, we only have to change the slope of the cones that we constructed, and the results go through.

We also considered other variations of the problems that arise by combining different criteria, and also the problem related to the farthest neighbor rule, instead of the nearest neighbor rule. For this version, an $O(n \log n)$-time algorithm has been proposed for the MAXCOV criterion. However, it is still an open problem if it is possible to process the input in a data structure (within $O(n \log n)$ time) such that the reverse farthest neighbor set for a query point can be answered in $O(\log n)$ time for the L_2 metric.

Finally, there are several natural problems for further research by considering other optimization problems, like for example, minimizing or maximizing the average or the sum of the distances to $\mathrm{BRNN}(b)$.

We recall that our methods and analyses were designed for the planar case exclusively. Adapting them to a higher-dimensional setting, even three dimensions, is a challenge.

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