

24th International Meshing Roundtable (IMR24)

# On Indecomposable Polyhedra and The Number of Steiner Points

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## Abstract

The existence of *indecomposable polyhedra*, that is, the interior of every such polyhedron cannot be decomposed into a set of tetrahedra whose vertices are all of the given polyhedron, is well-known. However, the geometry and combinatorial structure of such polyhedra are much less studied. In this article, we investigate the structure of some well-known examples, the so-called *Schönhardt* polyhedron [10] and the Bagemihl's generalization of it [1], which will be called *Bagemihl's polyhedra*. We provide a construction of an additional point, so-called *Steiner point*, which can be used to decompose the Schönhardt and the Bagemihl's polyhedra. We then provide a construction of a larger class of three-dimensional indecomposable polyhedra which often appear in grid generation problems. We show that such polyhedra have the same combinatorial structure as the Schönhardt's and Bagemihl's polyhedra, but they may need more than one Steiner point to be decomposed. Given such a polyhedron with  $n \geq 6$  vertices, we show that it can be decomposed by adding at most  $\lceil \frac{n-5}{2} \rceil$  interior Steiner points. We also show that this number is optimal in the worst case.

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**Keywords:** Indecomposable polyhedron, Steiner point, Schönhardt polyhedron; Bagemihl's polyhedron, tetrahedralization

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## 1. Introduction

The existence of three-dimensional (non-convex) polyhedron whose interior cannot be decomposed into a set of non-overlapping tetrahedra without new vertices has long been observed [7]. In 1928, Schönhardt provided the simplest example, which is a twisted triangular prism with six vertices. It is now well-known as the *Schönhardt polyhedron* [10]. Later, further such non-convex, non-tetrahedralizable polyhedron with an arbitrary number of vertices have been presented, see [1,3,8]. Among them, Bagemihl's construction [1] is a direct generalization from the Schönhardt's construction.

The existence of indecomposable polyhedra is a major difficulty in many geometric and combinatorial problems. For example, Below shows that the complexity of finding minimal or maximal subdivisions of three-dimensional polyhedra are NP-hard [2]. Rupert and Seidel show that to determine whether a given three-dimensional polyhedron can be decomposed or not is NP-complete [9]. The Schönhardt polyhedron appears as an important example in the

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study of the flip-graph of all triangulations of a given point set [4]. In 3d tetrahedral mesh generation, indecomposable polyhedra are the main obstacles in the design and proof of several key algorithms, such as the recovery of a non-existing edge and the deletion of an existing vertex, see e.g. [5,6,11,12].

When tetrahedralizing an indecomposable polyhedron, it is necessary to add additional points, the so-called *Steiner points*<sup>1</sup>. It is easy to show that the Schönhardt polyhedron needs at most one Steiner point. However, Chazelle constructed a polyhedron that may need as many as  $\Omega(n^2)$  Steiner points. We can treat the Schönhardt polyhedron and Chazelle's polyhedron as the two extreme cases for the number of Steiner points. Surprisingly enough, very few works about the number of Steiner points between  $O(1)$  and  $O(n^2)$  is known. The question we are going to investigate in this article is,

*Given a 3d indecomposable polyhedron, how many Steiner points are necessary to decompose it?*

In order to answer this question, it is necessary to understand the geometry and the combinatorial structure of the given polyhedron.

In this paper, we first study this question for the class of polyhedra constructed by Bagemihl [1], which is a generalisation of the Schönhardt polyhedron. Hereafter we will call them *Bagemihl's polyhedra* (described in Section 2.1). A Bagemihl's polyhedron can have arbitrary number of vertices. Due to its structural properties, we show that a Bagemihl's polyhedron needs only one interior Steiner point to be decomposed. Our proof is based on a construction of a Steiner point in the interior of a given Bagemihl's polyhedron, and we prove that all boundary faces of this polyhedron are visible by this Steiner point (in Section 2.2). Furthermore, we show that our constructed Steiner point is also valid for a class of *generalized Bagemihl's polyhedra* which can be obtained by relaxing the symmetric and height requirements in Bagemihl's construction (in Section 2.3).

Next, in Section 3, we first extends Bagemihl's Theorem to show that there exists a larger class of indecomposable polyhedra (in Section 3.1). We then give a general construction of such polyhedra with  $n \geq 6$  vertices, denoted as  $\sigma_n$ . It is worth mentioning, that the polyhedra from our construction are commonly encountered during the process of tetrahedral mesh generation. We show that our constructed polyhedra have the same combinatorial structure as the Schönhardt's and Bagemihl's polyhedra, but they may need more than one interior Steiner point to be decomposed (in Section 3.2). We then prove the following main result regarding the number of Steiner points for our constructed polyhedra (in Section 3.3):

*Given a polyhedron  $\sigma_n$  that satisfies our construction, where  $n$  is the number of vertices of  $\sigma_n$ , it needs at most  $\lceil \frac{n-5}{2} \rceil$  interior Steiner points to be decomposed.*

Our proof of this result is based on a construction of Steiner points in the interior of such polyhedra so that it can be decomposed into a set of tetrahedra with the help of these Steiner points. This construction also provides hints to design efficient algorithms to tetrahedralise such polyhedron.

Finally, some closing remarks and open questions are given in Section 4.

## 2. Bagemihl's Polyhedra and a Construction of a Steiner Point

In the Paper "On Indecomposable Polyhedra" by F. Bagemihl ([1]) he proves the following theorem.

**Theorem 1** ([1]). *If  $n$  is an integer not less than 6, then there exists a polyhedron,  $\pi_n$ , with  $n$  vertices and the following properties:*

- (I)  $\pi_n$  is simple and every one of its faces is a triangle.
- (II) If  $\tau$  is a tetrahedron, each of whose vertices is a vertex of  $\pi_n$ , then not every interior point of  $\tau$  is an interior point of  $\pi_n$ .

<sup>1</sup> There exist several types of Steiner points, named after Jakob Steiner (1796 – 1863), a Swiss mathematician who worked primarily in geometry, in the literatures, like the Steiner points in the Steiner tree problem, see e.g. [http://en.wikipedia.org/wiki/Steiner\\_tree\\_problem](http://en.wikipedia.org/wiki/Steiner_tree_problem), and the Steiner point in a triangle, see e.g. [http://en.wikipedia.org/wiki/Steiner\\_point\\_\(triangle\)](http://en.wikipedia.org/wiki/Steiner_point_(triangle)). The Steiner points in this article are constructed for decomposing Schönhardt or other indecomposable polyhedra. They are different to the previous ones.

- (III) Every open segment whose endpoints are vertices of  $\pi_n$ , but which is not an edge of  $\pi_n$ , lies wholly exterior to  $\pi_n$ .
- (IV) Every triangle whose sides are edges of  $\pi_n$  is a face of  $\pi_n$ .

**Comments.** In the original version of Theorem 1 [1], Bagemihl only stated the first three properties, (I), (II), and (III). However, he gave a construction of a class of polyhedra which also fulfills the property (IV). Note that by including the property (IV), we might decrease the size of the original class of polyhedra. But this is out of the scope of this article. With the included property (IV), the property (II) becomes redundant. It is followed together from (I), (III) and (IV).

Note that the property (II) indicates that  $\pi_n$  is indecomposable, since no tetrahedron  $\tau$  whose vertices are from  $\pi_n$  in the interior of  $\pi_n$  exists. The key fact is that  $\tau$  must contain at least one open segment of  $\pi_n$ . Suppose the four edges of  $\tau$  are all not open segments, then, by (IV), the boundary of  $\pi_n$  must form a tetrahedron. Since  $\pi_n$  is simple by (I), we can conclude that  $\pi_n$  is a tetrahedron. But this is contradict to the assumption  $n \geq 6$ . Then by (III),  $\tau$  does not lie the interior of  $\pi_n$ .

Bagemihl provides a construction of a class of polyhedra that satisfy Theorem 1, which will be called *Bagemihl’s polyhedra*.

In this section, we will first review the construction of Bagemihl’s polyhedra. Our goal is to show that a Bagemihl’s polyhedron needs only one Steiner point to be decomposed. For this purpose, we first give a construction of a Steiner point in a given Bagemihl’s polyhedron. We then prove it is valid for the decomposition. We further prove that our Steiner point is also valid for a variation of Bagemihl’s polyhedra by relaxing the symmetry and edge length requirements in the original Bagemihl’s construction.

### 2.1. Description of Bagemihl’s Polyhedra

Bagemihl’s construction starts with the Schönhardt polyhedron  $\pi_6$  which we will describe first. Take an equilateral triangle with edge lengths 1 and vertices  $A_1, B_1, C_1$ . Take a copy of it and lift it up orthogonally to the height  $h = 1$  and rotate it around the axis connecting the centers of the top and bottom triangle by an angle of  $\theta = 30^\circ$ . Call the so obtained vertices in the top triangle  $A_2, B_2, C_2$ , respectively. By connecting the vertices as shown in Figure 1 we obtain the polyhedron  $\pi_6$ .

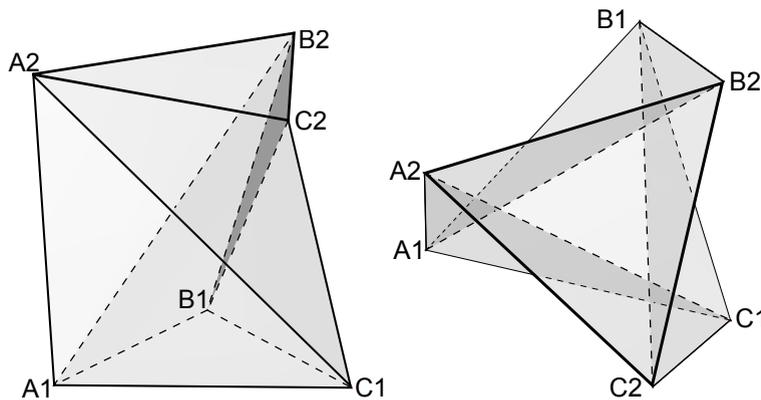


Fig. 1. The Schönhardt polyhedron, which is the Bagemihl’s polyhedron  $\pi_6$ . A side view (left) and a top view (right) are shown.

For the case  $n > 6$ , Bagemihl adds an open circular arc  $\widehat{A_1A_2}$  connecting  $A_1$  and  $A_2$  in the interior of  $\pi_6$ . The radius of this arc is chosen to be large enough such that every point of  $\widehat{A_1A_2}$  is on the same side of the plane  $C_1A_2C_2$  as  $A_1$ , and on the same side of the plane  $B_1A_1B_2$  as  $A_2$ . On the arc  $\widehat{A_1A_2}$  one can choose  $k = n - 6$  distinct points,  $D_1, D_2, \dots, D_k$ , in the order  $A_1D_1D_2 \dots D_{k-1}D_kA_2$  and add the edges  $A_1D_1, D_1D_2, \dots, D_{k-1}D_k, D_kA_2$  connecting the vertices. An example of a  $\pi_9$  is shown in Figure 2.

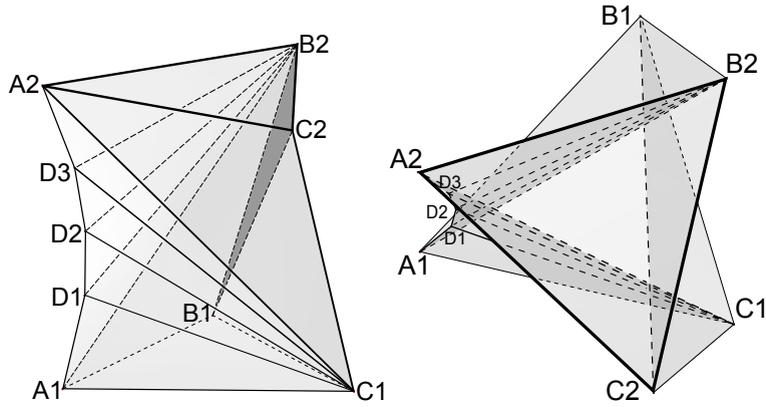


Fig. 2. A Bagemihl's polyhedron  $\pi_9$ . A side view (left) and a top view (right) are shown.

### 2.2. Construction of a Steiner Point

Given a Bagemihl's polyhedron,  $\pi_n$  with  $n \geq 6$  vertices, it is clear that at least one Steiner point is needed. But it is not obvious how many Steiner points are necessary. We want to show that one Steiner point is already sufficient. In this section, we give a construction of such a Steiner point.

We first consider  $\pi_6$ , which is just the Schönhardt polyhedron. The region in which we can place a Steiner point is the intersection of the eight halfspaces defined by the boundary triangles of the Schönhardt polyhedron, see Figure 3.

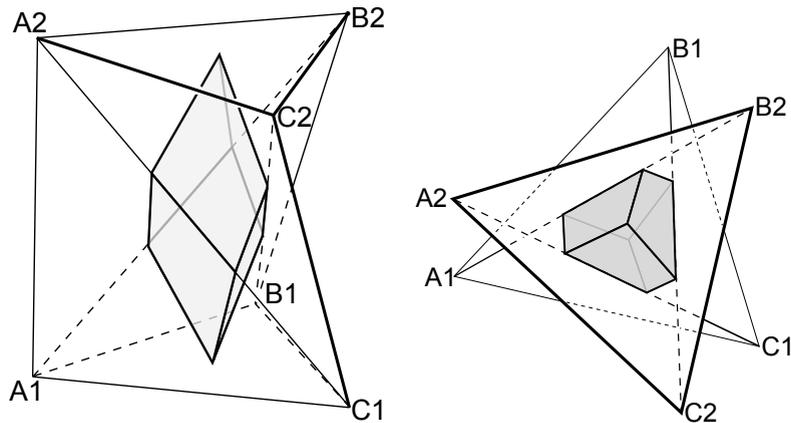


Fig. 3. The (open) valid domain for placing Steiner points inside the Schönhardt polyhedron. A side view (left) and a top view (right) are shown.

Placing the points  $D_1, \dots, D_k$ , where  $k = n - 6$ , in the interior of  $\pi_6$  just as described by Bagemihl, the region for a Steiner point  $S$  in  $\pi_n$  is getting smaller. We want to show that it is not empty for all  $k \in \mathbb{N}_{\geq 0}$  and all choices of additional points  $D_i$ . For this purpose we will show that it is always possible to place a Steiner point in the interior that has the required visibility properties.

We first determine the domain in which the valid arcs as described by Bagemihl can live. First, every arc has to lie inside  $\pi_6$ , so it is restricted by the halfspaces limited by the faces  $A_1A_2C_1$  and  $A_1A_2B_2$ , respectively. Since every point of an open arc  $\widehat{A_1A_2}$  has to be on the same side of the plane  $C_1A_2C_2$  as  $A_1$ , and on the same side of the plane  $B_1A_1B_2$  as  $A_2$  [1, p. 413], it is restricted by these two faces of  $\pi_6$  as well. So, this domain is the intersection of four halfspaces, which is a tetrahedron (see Figure 4), denoted as  $T$ , with vertices  $A_1A_2G_1G_2$ , where  $G_1$  and  $G_2$  are defined by

$$G_1 := \text{plane}_{C_1A_2C_2} \cap \text{line}_{A_1B_2}$$

$$G_2 := \text{plane}_{B_1A_1B_2} \cap \text{line}_{A_2C_1}.$$

Note that the points  $G_1$  and  $G_2$  are on the boundary of  $\pi_6$ : Since the polyhedron doesn't have interior edges, the points  $A_1$  and  $B_2$  will lie on different sides of the plane through  $C_1A_2C_2$ , so  $G_1$  has to be on the edge  $A_1B_2$  itself. Analogously  $G_2$  has to be on the edge  $A_2C_1$ .

With the help of this tetrahedron  $T$ , we can determine the locations for the intersections of the tangent lines of all possible arcs at  $A_1$  and  $A_2$ . Given a possible arc  $\widehat{A_1A_2}$  (as defined by Baghmil) in the tetrahedron  $T$ , define the intersection point of the tangent lines through  $A_1$  and  $A_2$  to the arc  $\widehat{A_1A_2}$  as  $P$  (refer to Figure 4).  $P$  must lie in the closure of  $T$ . If the radius of the circle (containing the arc) is getting larger, the distance between  $P$  and the line through  $A_1$  and  $A_2$  will decrease.

It is enough to consider the extremal case, i.e. the case when the radius of the circle is the smallest possible.

Consider the points  $G_1$  and  $G_2$ . By definition, they can see all vertices of  $\pi_n$  or are coplanar with a face containing them. The open segment  $G_1G_2$  is obtained by first intersecting the two planes through  $C_1A_2C_2$  and  $B_1A_1B_2$ , then by intersecting the interior of  $\pi_6$ . All points in the interior of the open segment  $G_1G_2$  can see all interior points of  $\pi_n$ , but we cannot take a point on this segment as a Steiner point because of the coplanarity with some faces, however we are already close to it.

Now construct the Steiner point  $S$  as follows. Intersect the plane  $p_1$  containing the arc  $\widehat{A_1A_2}$  with the line passing through  $G_1$  and  $G_2$ . We obtain a point  $\tilde{S}$  in the interior of  $\pi_n$ . Now construct a plane  $p_2$  which is orthogonal to the line passing through  $A_1$  and  $A_2$  and containing  $\tilde{S}$ . Intersect the planes  $p_1$  and  $p_2$ . We obtain a line which we will call  $l$ . By construction  $\tilde{S} \in l$ . Now take the point  $\tilde{S}$  and move it a little on the line  $l$  away from  $\widehat{A_1A_2}$  but only so far, that it is still before the edge connecting  $B_1$  with  $C_2$ . The so obtained point is our Steiner point  $S$ , refer to Figure 4.

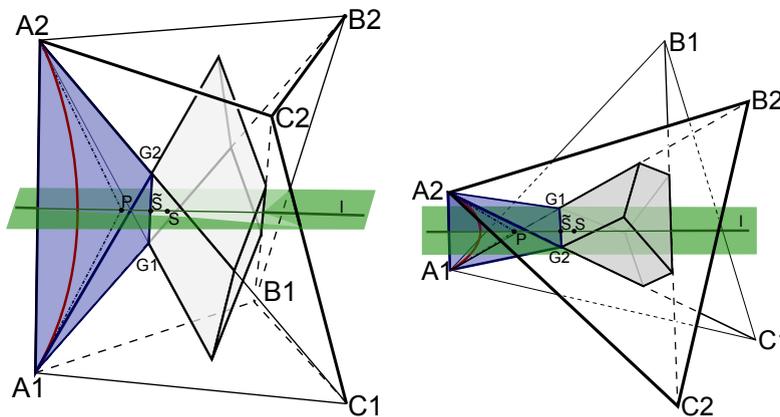


Fig. 4. The tetrahedron  $A_1A_2G_1G_2$  in which the arc in Bagemihl's construction can lie is shown in blue. An example of such an arc  $\widehat{A_1A_2}$  is also displayed in red. This arc cannot lie on a boundary face of the tetrahedron. The construction of a Steiner point  $S$  in  $\pi_n$  is also illustrated. The plane  $p_1$  (not shown) contains the arc  $\widehat{A_1A_2}$  and the plane  $p_2$  (green) is orthogonal to the line passing  $A_1A_2$ . One can see the line  $l := p_1 \cap p_2$  and the points  $P, \tilde{S}, S \in l$ .

**Proposition 2.** *A Bagemihl's polyhedron  $\pi_n$  with  $n$  vertices together with the constructed Steiner point  $S \in \pi_n$  can be tetrahedralized.*

*Proof.* By our construction,  $S$  lies beyond  $P$ . Recall that  $P$  is the intersection point of the tangent lines of the arc at  $A_1$  and  $A_2$ , see Figure 5. By that, the vertices  $A_1, D_1, \dots, D_k, A_2$  are visible by  $S$  (from the interior of  $\pi_n$ ).

The visibility of the remaining vertices  $C_1, C_2, B_1$  and  $B_2$  is given, since  $S$  is chosen by moving  $\tilde{S}$  to the inside of the visible polytope of  $\pi_n$ . The point  $\tilde{S}$  lies on the boundary of the visible domain of the polytope  $\pi_n$  (and not only the polytope  $\pi_6$ ). This polytope is as well bounded by the edge  $B_1C_2$ , so we can be sure that there is space left in the interior. □

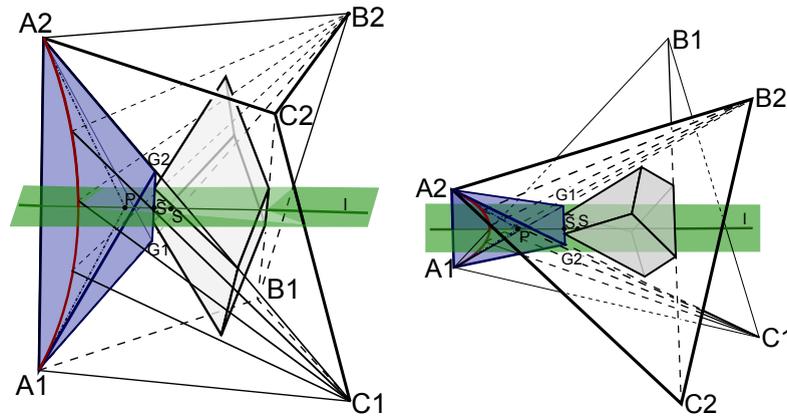


Fig. 5. An example of the constructed Steiner point  $S \in \pi_9$ . The smaller polyhedron in the interior is the valid domain for  $\pi_9$ .

### 2.3. Generalized Bagemihl's Polyhedra

Bagemihl gave the construction of a special class of polyhedra without leaving much space of freedom. The only choice one has is the one arc lying inside the original Schönhardt polyhedron which even has to fulfill some visibility constraints and the points one chooses on the arc. We can generalize these polyhedra without losing their main properties, i.e. they will still fulfill the properties (I)-(IV) of Theorem 1.

A similar way to generalize them is to let the rotation angle  $\vartheta$  of the triangles be in  $\vartheta \in (0^\circ, 60^\circ)$  instead of fixing it to a value of  $\vartheta = 30^\circ$ . At an angle of  $\vartheta = 0^\circ$  the polyhedron is a prism and so doesn't fulfill the properties of the Theorem as well as in the case  $\vartheta = 60^\circ$  in which the polyhedron separates into two parts which are attached at a single point, so the polyhedron isn't simple any more. Another way is to let the height  $h$  of the polyhedron be arbitrary in  $h \in \mathbb{R}_{>0}$  instead of fixing it to the value of  $h = 1$ .

One can even change the bottom and top triangle itself. It is not necessary that they are parallel, are equilateral or have the same size. One can construct a generalized form of Bagemihl polyhedra based on two triangles in space connecting the vertices like in the original case. As long as they fulfill the properties of his Theorem and the open circular arc has the same visibility properties as in the original case, we will call them *generalized Bagemihl's polyhedra*. See Figure 6 for an example.

These polyhedra are still not decomposable, so at least one Steiner point is needed. But the construction of a Steiner point given above can be adapted to this class of polyhedra, so we can state the following Corollary. In Figure 6 the visible polytope of the example polyhedron is shown as well.

**Corollary 3.** For a tetrahedralization of  $\tilde{\pi}_n$  with  $n \in \mathbb{N}_{\geq 6}$  one needs exactly one Steiner point, where  $\tilde{\pi}_n$  is a generalized Bagemihl's polyhedron as described above.

*Proof.* Since the property (II) mentioned in Theorem 1 is still fulfilled, at least one Steiner point is needed. On the other hand, one can use the construction as described in section 2.2 to obtain a Steiner point  $S$  in  $\tilde{\pi}_n$ . Furthermore, the proof of Proposition 2 can be adapted to show that  $S$  is already sufficient to tetrahedralize  $\tilde{\pi}_n$ .  $\square$

## 3. A Larger Class of Indecomposable Polyhedra and The Number of Steiner Points

In this section, we first extend Bagemihl's Theorem to show that there exists a larger class of indecomposable polyhedra. We then provide a different construction of one of such polyhedra. We show that our constructed polyhedra are combinatorially the same as the Schönhardt and Bagemihl's polyhedra. But they may require more than one Steiner point to be decomposed. We then prove the maximum number of necessary Steiner points is  $\lfloor \frac{n-5}{2} \rfloor$ . Our proof is based on a construction of such Steiner points in the interior.

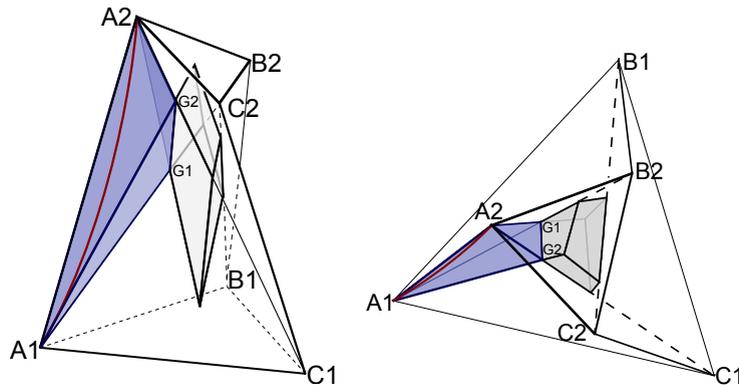


Fig. 6. Two views of an example of a generalized Bagemihl's polyhedron  $\tilde{\pi}_6$ . One still can add more vertices on the chosen suitable arc that is shown in red. The visible polytope is illustrated in a light blue, while the tetrahedron as the possible domain for arcs is illustrated in a darker blue to the left.

### 3.1. A Larger Class of Indecomposable Polyhedra

Note that Bagemihl's polyhedra  $\pi_n$  all satisfy a crucial property, which is (III) in Theorem 1, i.e., every open segment whose endpoints are vertices of  $\pi_n$ , but which is not an edge of  $\sigma_n$ , lies wholly exterior to  $\pi_n$ . This property is sufficient but not necessary to guarantee that a polyhedron is indecomposable. By relaxing this property, we can obtain a larger class of indecomposable polyhedra. Their properties are given in the following Theorem. The only difference to Theorem 1 is the property (III), which is also highlighted.

**Theorem 4.** *If  $n$  is an integer not less than 6, then there exists a polyhedron,  $\sigma_n$ , with  $n$  vertices and the following properties:*

- (I)  $\sigma_n$  is simple and every one of its faces is a triangle.
- (II) If  $\tau$  is a tetrahedron, each of whose vertices is a vertex of  $\sigma_n$ , then not every interior point of  $\tau$  is an interior point of  $\sigma_n$ .
- (III) **Every open segment  $e$ , whose endpoints are vertices of  $\sigma_n$ , but which is not an edge of  $\sigma_n$ , satisfies  $e \cap \sigma_n \neq e$ .**
- (IV) Every triangle whose sides are edges of  $\sigma_n$  is a face of  $\sigma_n$ .

*Comment.* The property (II) is redundant, since it can be derived from the other three properties. We keep it in order to keep the same form of Theorem 1.

The arguments that  $\sigma_n$  is an indecomposable polyhedron are exactly the same as those given by Bagemihl (see Section 2). The key fact is that every tetrahedron  $\tau$  whose vertices in  $\sigma_n$  must contain at least one open segment. By the relaxed property (III), it is sufficient to ensure that some points of  $\tau$  do not lie in the interior of  $\sigma_n$ .

### 3.2. A Construction of $\sigma_n$

Choose four non-coplanar points  $\mathbf{a}, \mathbf{b}, \mathbf{c}, \mathbf{d} \in \mathbb{R}^3$ , and a (simple) curve  $\gamma$  starting at  $\mathbf{c}$  and ending at  $\mathbf{d}$ , and  $\gamma$  lies in the intersection of the two open halfspaces bounded by the triangles  $\mathbf{cda}$  and  $\mathbf{dcb}$  (using the righthand-rule to oriented the triangles), refer to Figure 7 (a).

Now we will choose  $k + 2$  ( $k \geq 0$ ) distinct points, denoted as  $\mathbf{g}_0, \dots, \mathbf{g}_{k+1}$ , on the curve  $\gamma$  from  $\mathbf{c}$  to  $\mathbf{d}$ , so that they all satisfy the following constraints (refer to Figure 7):

- (c1) The line segment  $\mathbf{cd}$  intersects all the triangles  $\mathbf{abg}_i$ ,  $i = 0, \dots, k + 1$ .
- (c2) Given two adjacent points  $\mathbf{g}_i$  and  $\mathbf{g}_{i+1}$ , for  $i = 0, \dots, k$ , on the curve  $\gamma$ , the point  $\mathbf{g}_{i+1}$  and  $\mathbf{d}$  must lie in the same halfspace bounded by the plane containing  $\mathbf{abg}_i$ .

(1)	$(\mathbf{a}, \mathbf{c}, \mathbf{d}), (\mathbf{b}, \mathbf{c}, \mathbf{d})$
(2)	$(\mathbf{a}, \mathbf{c}, \mathbf{g}_0), (\mathbf{b}, \mathbf{c}, \mathbf{g}_0), (\mathbf{a}, \mathbf{d}, \mathbf{g}_{k+1}), (\mathbf{b}, \mathbf{d}, \mathbf{g}_{k+1})$
(3)	$(\mathbf{a}, \mathbf{g}_i, \mathbf{g}_{i+1}), (\mathbf{b}, \mathbf{g}_i, \mathbf{g}_{i+1})$ where $i = 0, \dots, k$

Table 1. The set of boundary faces of  $\sigma_n$ .

	$\mathbf{a}$	$\mathbf{b}$	$\mathbf{c}$	$\mathbf{d}$	$\mathbf{g}_0$	$\mathbf{g}_1$	$\mathbf{g}_2$	$\mathbf{g}_3$	$\mathbf{g}_4$
$x$	-5	5	0	0	1	-2.5	2	-2.5	1
$y$	0	0	-10	10	-8	-4	0	4	8
$z$	0	0	2	2	4	4	4	4	4

Table 2. The coordinates of the vertices of a  $\sigma_9$ .

- (c3) Let  $\mathbf{g}_i$  and  $\mathbf{g}_j$ , for  $i, j = -1, \dots, k + 2$  and  $i \neq j$ , be two non-adjacent points on the curve  $\gamma$  where  $\mathbf{g}_{-1} := \mathbf{c}$  and  $\mathbf{g}_{k+2} := \mathbf{d}$ . Without loss of generality, assume  $i < j$ . Then the line segment  $\mathbf{g}_i\mathbf{g}_j$  (except  $\mathbf{g}_{-1}\mathbf{g}_{k+2} = \mathbf{cd}$ ) does not intersect all triangles  $\mathbf{abg}_l$ , where  $i < l < j$ .
- (c4) Let  $\mathbf{g}_i, \mathbf{g}_{i+1}$  and  $\mathbf{g}_{i+2}$ , for  $i = -1, \dots, k$ , be three consecutive points on the curve  $\gamma$ . Then the three points are neither coplanar with  $\mathbf{a}$  nor  $\mathbf{b}$ .

Now the polyhedron  $\sigma_n, n = 6 + k$ , where  $k \geq 0$ , is constructed by choosing the boundary faces listed in Table 1 (refer to Figure 7):

*Comments.* The curve  $\gamma$  in our construction is only an assistant. One can construct  $\sigma_n$  by simply choosing  $k$  points that satisfy all constraints. However, it is easier to imagine the relations of the points  $\mathbf{g}_i$  with a curve in mind. The condition (c4) ensures that all faces of  $\sigma_n$  are triangles.

Figure 7 gives an example of such polyhedron,  $\sigma_9$ . A particular choice of the coordinates of the 9 vertices are given in the Table 2.

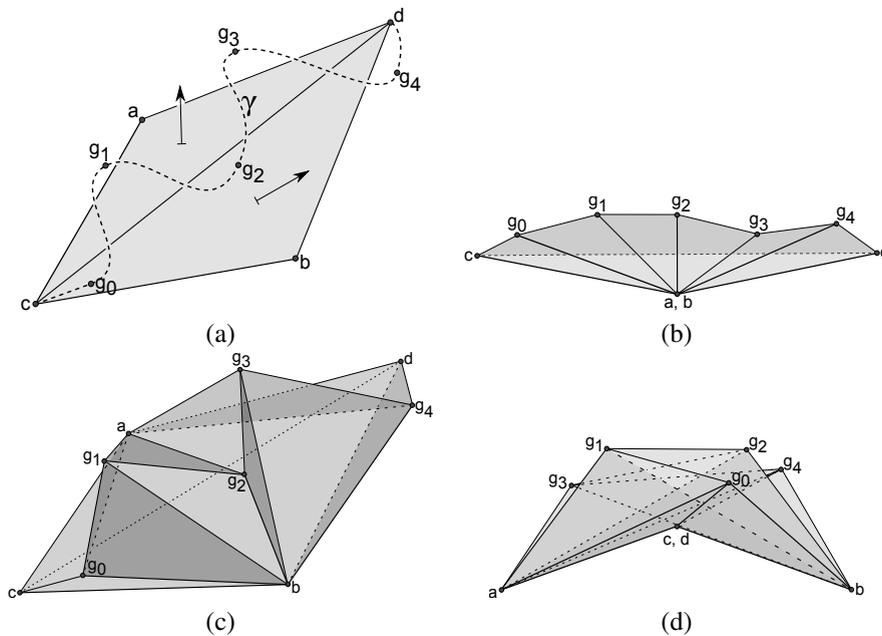


Fig. 7. An example polyhedron,  $\sigma_9$ , with 9 vertices. The four initial points  $\mathbf{a}, \mathbf{b}, \mathbf{c}, \mathbf{d}$  as well as the points  $\mathbf{g}_i, i = 0, \dots, 4$  chosen from a curve  $\gamma$  are shown in (a). Pictures (b), (c), and (d) are different views of the constructed polyhedron  $\sigma_9$ . A particular choice of the coordinates of the vertices is given in Table 2.

In the following we show that the so constructed polyhedron  $\sigma_n$  satisfies the properties (I) - (IV) in Theorem 4. At first, we show that  $\sigma_n$  is a simple 3d polyhedron. Let  $\mathcal{T}$  be the set of tetrahedra

$$\mathcal{T} = \{\mathbf{abcg}_0, \mathbf{abdg}_{k+1}\} \cup \{\mathbf{abg}_i\mathbf{g}_{i+1} \mid i = 0, \dots, k\}.$$

The constraint (c2) ensures that every two tetrahedra in  $\mathcal{T}$  must either share a common face or only share the common edge  $\mathbf{ab}$ . We see that the union of the set of tetrahedra of  $\mathcal{T}$  is a 3d simple polyhedron  $P := \cup \mathcal{T}$ . By constraint (c1), we see that the open line segment  $\mathbf{cd}$  lies wholly in the interior of  $P$ . Moreover, this constraint also ensures that the two open triangles  $\mathbf{cda}$  and  $\mathbf{dcb}$  lie wholly in the interior of  $P$ . Finally, by removing the tetrahedron  $\mathbf{abcd}$  from  $P$  we obtain the polyhedron  $\sigma_n$ .

Next we show that it is combinatorially equivalent to the Bagemihl's polyhedron  $\pi_n$ . The simplest case is when  $n = 6$  ( $k = 0$ ). The corresponding  $\pi_6$  is just the well-known Schönhardt polyhedron (refer to Figure 1). The 6 vertices of  $\sigma_6$  are:  $\mathbf{a}, \mathbf{b}, \mathbf{c}, \mathbf{d}, \mathbf{g}_0, \mathbf{g}_1$ , respectively. We map them one-to-one to the vertices of the Schönhardt polyhedron as following (see Figure 8 Left):

- $\mathbf{g}_0 \rightarrow A_1, \mathbf{c} \rightarrow B_1, \mathbf{b} \rightarrow C_1$ ; and
- $\mathbf{g}_1 \rightarrow A_2, \mathbf{a} \rightarrow B_2, \mathbf{d} \rightarrow C_2$ .

In general, when  $n \geq 6$  ( $k \geq 0$ ), the  $n$  vertices of  $\sigma_n$  are:  $\mathbf{a}, \mathbf{b}, \mathbf{c}, \mathbf{d}, \mathbf{g}_0, \mathbf{g}_1, \dots, \mathbf{g}_{k+1}$ , respectively. We build a one-to-one map between the vertices of  $\sigma_n$  and the Bagemihl's polyhedron  $\pi_n$  as following (refer to Figure 8 Right):

- $\mathbf{g}_0 \rightarrow A_1, \mathbf{c} \rightarrow B_1, \mathbf{b} \rightarrow C_1$ ;
- $\mathbf{g}_{k+1} \rightarrow A_2, \mathbf{a} \rightarrow B_2, \mathbf{d} \rightarrow C_2$ ; and
- $\mathbf{g}_i \rightarrow D_i$ , for all  $i = 1, \dots, k$ .

By this mapping, one can check that the faces of  $\sigma_n$  and  $\pi_n$  are also mapped one-to-one, so do the edges of them.

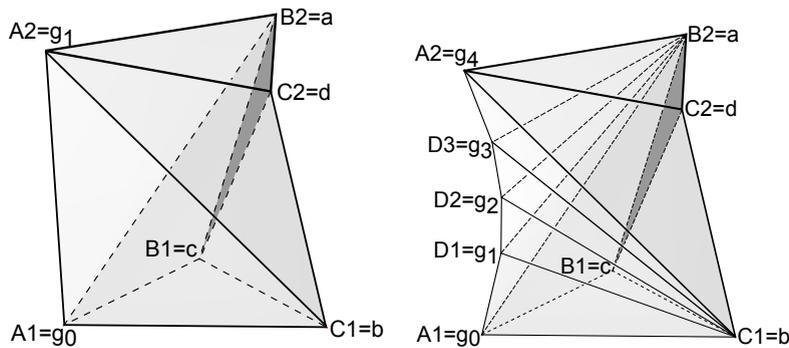


Fig. 8. The mapping between the vertices of  $\sigma_n$  and the vertices of the Bagemihl's polyhedron  $\pi_n$ .

Now we can show that  $\sigma_n$  satisfies the properties in Theorem 4 by borrowing Bagemihl's arguments in proving Theorem 1 [1].

At first,  $\sigma_n$  satisfies the properties (I) and (IV) by a direct checking of the faces (listed above) and the edges of  $\sigma_n$ , using (c3) and (c4). Note that the property (IV) is fulfilled because of the constraint (c3) which prohibits to have three consecutive points  $\mathbf{g}_i, \mathbf{g}_{i+1}, \mathbf{g}_{i+2}$  being collinear and constraint (c4) ensures the triangularity of the faces.

Remember that the main reason that causes  $\sigma_n$  to be indecomposable is the property (II), since no open tetrahedron  $\tau$  whose vertices of  $\sigma_n$  can lie in the interior of  $\sigma_n$ . The key fact is that  $\tau$  must contain an open segment as stated in the property (III). This fact is true by the properties (I), (III) and (IV).

What remains is to show that  $\sigma_n$  satisfies the property (III). The open segments of  $\sigma_n$  are the line segment  $\mathbf{ab}$ , and all line segments with endpoints  $\mathbf{g}_i\mathbf{g}_j$ , where  $\mathbf{g}_i$  and  $\mathbf{g}_j$  are not adjacent vertices on the curve  $\gamma$ , where  $i, j = -1, 0, \dots, k+2$  and  $i \neq j$ , except the line segment  $\mathbf{cd} = \mathbf{g}_{-1}\mathbf{g}_{k+2}$ . The constraint (c3) in our construction ensures that such a line segment must not lie wholly in the interior of  $\sigma_n$ . This shows that the property (III) is satisfied.

### 3.3. The Number of Steiner Points for $\sigma_n$

From now on, we study the question: “Given a  $\sigma_n$ , how many Steiner points are necessary to decompose it?”

At first, we show that a  $\sigma_n$  may need more than one Steiner point to be decomposed. We provide an explicit example of a  $\sigma_9$ . The geometry of this polyhedron is similar to the one shown in Figure 7. The coordinates of the 9 vertices are given in the Table 2.

Given an arbitrary  $\sigma_n$ , we can associate every pair of its triangles,  $\mathbf{g}_i\mathbf{g}_{i+1}\mathbf{a}$  and  $\mathbf{g}_i\mathbf{g}_{i+1}\mathbf{b}$ , to an interval,  $\mathbf{t}_{a,i}\mathbf{t}_{b,i}$ , on the line through  $\mathbf{cd}$ , for all  $i = 0, 1, \dots, k$ , where:

$$\begin{aligned} \mathbf{t}_{a,i} &:= \text{plane}_{\mathbf{g}_i\mathbf{g}_{i+1}\mathbf{a}} \cap \text{line}_{\mathbf{cd}} \\ \mathbf{t}_{b,i} &:= \text{plane}_{\mathbf{g}_i\mathbf{g}_{i+1}\mathbf{b}} \cap \text{line}_{\mathbf{cd}}. \end{aligned}$$

Any point  $\mathbf{p}$  in the interval  $\mathbf{t}_{a,i}\mathbf{t}_{b,i}$  must see the two triangles,  $\mathbf{g}_i\mathbf{g}_{i+1}\mathbf{a}$  and  $\mathbf{g}_i\mathbf{g}_{i+1}\mathbf{b}$ , from the interior of  $\sigma_n$ . However, if  $\mathbf{p}$  does not lie in the interval defined by a pair of triangles,  $\mathbf{p}$  can not see them.

In general, such an interval is not necessarily inside the line segment  $\mathbf{cd}$  for an arbitrary  $\sigma_n$ . In our particular example (in Table 2), the pair of planes containing the triangles  $\mathbf{g}_i\mathbf{g}_{i+1}\mathbf{a}$  and  $\mathbf{g}_i\mathbf{g}_{i+1}\mathbf{b}$  cut the line segment  $\mathbf{cd}$  in its interior, for all  $i = 0, 1, 2, 3$ . Furthermore, the two intervals  $\mathbf{t}_{a,0}\mathbf{t}_{b,0}$  and  $\mathbf{t}_{a,3}\mathbf{t}_{b,3}$  are disjoint. This implies that one cannot find a common interior Steiner point that is visible simultaneously by the four triangles, which are  $\mathbf{g}_0\mathbf{g}_1\mathbf{a}$ ,  $\mathbf{g}_0\mathbf{g}_1\mathbf{b}$ ,  $\mathbf{g}_3\mathbf{g}_4\mathbf{a}$ , and  $\mathbf{g}_3\mathbf{g}_4\mathbf{b}$ . Hence, more than one Steiner point is needed for decomposing this polyhedron.

For a general  $\sigma_n$  with  $n$  vertices, there are  $k + 1$  intervals. It is easy to estimate that the required number of Steiner points for decomposing  $\sigma_n$  will not exceed the total number of such intervals, which is  $k + 1 = n - 5$ . However, this estimate is too rough. By an careful construction of Steiner points, one can get an explicit upper bound on the number of Steiner points for any  $\sigma_n$ . It is given by the following Theorem.

**Theorem 5.** *Given a 3d polyhedron  $\sigma_n$  with  $n$  vertices, it can be decomposed by adding  $\lceil \frac{n-5}{2} \rceil$  interior Steiner points.*

*Proof.* We prove it in two steps: at first, we will place this number of Steiner points in the interior of the  $\sigma_n$ , then we show how to tetrahedralise it with these Steiner points.

*Step (1), placing Steiner points.* From the previous analysis, we see that the requirement of multiple Steiner points comes from the fact that one may not find a common Steiner point that is simultaneously visible by all boundary faces. We will place a number of Steiner points in the interior of  $\sigma_n$ . We make sure that each Steiner point that we place will be visible by a certain number of boundary faces, and every boundary face will be visible by at least one of these Steiner points.

Consider the  $k + 2$  vertices,  $\mathbf{g}_0, \mathbf{g}_1, \dots, \mathbf{g}_{k+1}$  of  $\sigma_n$ . Each  $\mathbf{g}_i$  ( $i = 0, 1, \dots, k + 1$ ) is a vertex of four adjacent boundary faces of  $\sigma_n$ , i.e.,  $\mathbf{g}_{i-1}\mathbf{g}_i\mathbf{a}$ ,  $\mathbf{g}_{i-1}\mathbf{g}_i\mathbf{b}$ ,  $\mathbf{g}_i\mathbf{g}_{i+1}\mathbf{a}$ , and  $\mathbf{g}_i\mathbf{g}_{i+1}\mathbf{b}$  (recall that  $\mathbf{g}_{-1} = \mathbf{c}$  and  $\mathbf{g}_{k+2} = \mathbf{d}$ ). We will search a point inside  $\sigma_n$  and near to  $\mathbf{g}_i$ , hence it is visible by all these four faces. For this purpose, it is not necessary to use all  $\mathbf{g}_i$ . In particular, we choose the following subset of the set of vertices of  $\sigma_n$ ,

$$\mathcal{G} := \{\mathbf{g}_1, \mathbf{g}_3, \mathbf{g}_5, \dots, \mathbf{g}_m\},$$

where the last index is

$$m = k + ((k + 1) \text{ modulo } 2),$$

which is the largest odd number of the indices. The cardinality  $|\mathcal{G}| = \lceil \frac{k+1}{2} \rceil$ .

Let  $\mathcal{G}^*$  be the set of points constructed from the points in  $\mathcal{G}$ , such that

$$\mathcal{G}^* := \{\mathbf{g}_j^* := \text{plane}_{\mathbf{g}_j\mathbf{ab}} \cap \text{line}_{\mathbf{cd}} \mid \mathbf{g}_j \in \mathcal{G}\},$$

see Figure 9. Note that the points in  $\mathcal{G}^*$  have the following visibilities from the inside of  $\sigma_n$ :

- (i) Each  $\mathbf{g}_j^*$ , where  $j = 1, 3, \dots, m$ , is visible by the faces  $\mathbf{ag}_{j-1}\mathbf{g}_j$ ,  $\mathbf{bg}_{j-1}\mathbf{g}_j$ ,  $\mathbf{ag}_j\mathbf{g}_{j+1}$ , and  $\mathbf{bg}_j\mathbf{g}_{j+1}$ ;
- (ii) Additionally,  $\mathbf{g}_1^*$  is visible by the two faces  $\mathbf{acg}_0$  and  $\mathbf{bcg}_0$ , and  $\mathbf{g}_m^*$  is visible by the two faces  $\mathbf{adg}_{k+1}$  and  $\mathbf{bdg}_{k+1}$ .

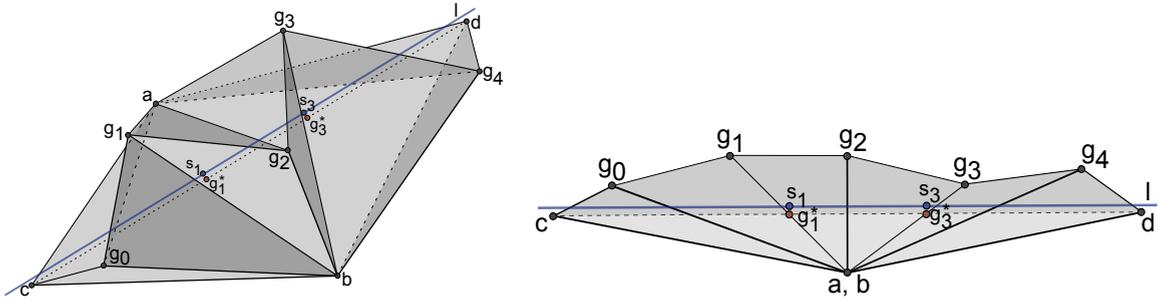


Fig. 9. Two views of the example polyhedron  $\sigma_9$  with the constructed points  $\mathcal{G}^*$  and the Steiner points  $\mathcal{S}$  on the common line  $l$  that is parallel to  $\mathbf{cd}$ .

(1)	$(\mathbf{a}, \mathbf{c}, \mathbf{d}), (\mathbf{b}, \mathbf{c}, \mathbf{d});$
(2)	$(\mathbf{a}, \mathbf{c}, \mathbf{s}_1), (\mathbf{b}, \mathbf{c}, \mathbf{s}_1), (\mathbf{a}, \mathbf{d}, \mathbf{s}_m), (\mathbf{b}, \mathbf{d}, \mathbf{s}_m);$
(3)	$\{(\mathbf{a}, \mathbf{s}_p, \mathbf{s}_{p+2}), (\mathbf{b}, \mathbf{s}_p, \mathbf{s}_{p+2}) \mid p = 1, 3, 5, \dots, m\}$

Table 3. The set of boundary faces of the remaining polyhedron.

Since all  $\mathbf{g}_j^*$ 's are on the line segment  $\mathbf{cd}$ , i.e., they are coplanar with the two faces  $\mathbf{cda}$  and  $\mathbf{cdb}$ , they are not yet our wanted Steiner points.

Now we will place our Steiner points moving from the set of points  $\mathcal{G}^*$ . Choose the plane  $p$  along the middle axis of the two planes containing the two bottom triangles  $\mathbf{cda}$  and  $\mathbf{cdb}$ .  $p$  must contain the line segment  $\mathbf{cd}$ . Now we will move  $\mathcal{G}^*$  within the plane  $p$  and toward the interior of  $\sigma_n$ . For our proof, we just move all points in such a way, that they all stay within a line, denoted as  $l$ , which is parallel to  $\mathbf{cd}$ . And we choose the moving distance small enough such that all the moving points remain in the interior of  $\sigma_n$  and their visibilities by faces given in (i) and (ii) do not change. We then take the set of points on the line as our Steiner points, denoted as

$$\mathcal{S} := \{s_j \mid s_j \text{ is moved from } \mathbf{g}_j^* \text{ onto } l, \mathbf{g}_j^* \in \mathcal{G}^*\},$$

then  $|\mathcal{S}| = \lceil \frac{k+1}{2} \rceil$ . See Figure 9 for an example.

Step (2), *tetrahedralising*  $\sigma_n$ . With the created Steiner points, we are able to create a tetrahedralisation of  $\sigma_n$ . The idea is first to remove tetrahedra from  $\sigma_n$  by using the set of Steiner points and the visibility properties of them, and second to tetrahedralise the remaining part, which is a 3d polyhedron with vertices  $\mathbf{a}, \mathbf{b}, \mathbf{c}, \mathbf{d}$ , and the set of Steiner points.

By the visibility properties (i) and (ii), we can remove the following sets of tetrahedra from  $\sigma_n$ :

$$\begin{aligned} \mathcal{T}_1 &:= \{\mathbf{ag}_{j-1}\mathbf{g}_j\mathbf{s}_j, \mathbf{bg}_{j-1}\mathbf{g}_j\mathbf{s}_j, \mathbf{ag}_j\mathbf{g}_{j+1}\mathbf{s}_j, \mathbf{bg}_j\mathbf{g}_{j+1}\mathbf{s}_j \mid \mathbf{s}_j \in \mathcal{S}\}, \\ \mathcal{T}_2 &:= \{\mathbf{acg}_0\mathbf{s}_1, \mathbf{bcg}_0\mathbf{s}_1, \mathbf{adg}_{k+1}\mathbf{s}_m, \mathbf{bdg}_{k+1}\mathbf{s}_m\}, \\ \mathcal{T}_3 &:= \{\mathbf{ag}_{p+1}\mathbf{s}_p\mathbf{s}_{p+2}, \mathbf{bg}_{p+1}\mathbf{s}_p\mathbf{s}_{p+2} \mid p = 1, 3, 5, \dots, m-2\}. \end{aligned}$$

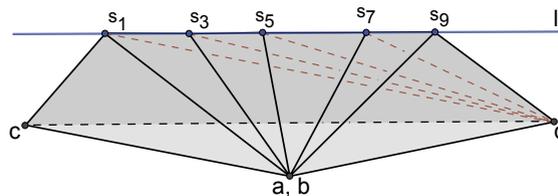


Fig. 10. The polyhedron after removing the sets  $\mathcal{T}_1, \mathcal{T}_2$  and  $\mathcal{T}_3$  of tetrahedra from  $\sigma_n$ . A decomposition of this polyhedron into the two sets  $\mathcal{T}_4$  and  $\mathcal{T}_5$  of tetrahedra is given. The internal edges are shown in brown.

The remaining region of  $\sigma_n$  after removing the above tetrahedra is a 3d polyhedron, see Figure 10 for an example. It has the vertices  $\{\mathbf{a}, \mathbf{b}, \mathbf{c}, \mathbf{d}\} \cup \mathcal{S}$ , and the boundary faces are given in Table 3. Since all Steiner points are collinear,

this polyhedron can be decomposed into the following two sets of tetrahedra:

$$\begin{aligned} \mathcal{T}_4 &:= \{\mathbf{acds}_1, \mathbf{bcds}_1\}, \\ \mathcal{T}_5 &:= \{\mathbf{as}_p\mathbf{s}_{p+2}\mathbf{d}, \mathbf{bs}_p\mathbf{s}_{p+2}\mathbf{d} \mid p = 1, 3, 5, \dots, m - 2\}. \end{aligned}$$

This concludes our proof. □

There are indeed many possibilities to place Steiner points that may lead to a smaller number of Steiner points. However, we can show that this number  $\lceil \frac{k+1}{2} \rceil = \lceil \frac{n-5}{2} \rceil$  of Steiner points is optimal in the worst case.

**Theorem 6.** *Given  $n \in \mathbb{N}_{\geq 6}$ , one can construct an a 3d polyhedron  $\sigma_n$  with  $n$  vertices which has the property that one needs exactly  $\lceil \frac{n-5}{2} \rceil$  interior Steiner points to decompose it.*

*Proof.* We prove the Theorem by giving a general construction of a  $\sigma_n$ , so that it will always need at least this number of Steiner points. We then get the equality by Theorem 5. The basic idea is to control the overlap of the intervals  $\mathbf{t}_{a,j}\mathbf{t}_{b,j}$ ,  $j = 0, \dots, n - 6$ , as defined at the beginning of section 3.3. By the following construction we ensure that two consecutive intervals  $\mathbf{t}_{a,j}\mathbf{t}_{b,j}$  and  $\mathbf{t}_{a,j+1}\mathbf{t}_{b,j+1}$  overlap in their interior. Moreover, if two non-consecutive intervals don't overlap, we will obtain the desired number of Steiner points.

Fix  $n \geq 6$  and start with non-coplanar points  $\mathbf{a}, \mathbf{b}, \mathbf{c}, \mathbf{d} \in \mathbb{R}^3$  as described in section 3.2. Then choose  $n - 4$  points  $\mathbf{g}_i$ ,  $i = 0, \dots, n - 5$  from the valid domain of a curve in a zig-zag shape, like in the polyhedron in Figure 7. By moving the points  $\mathbf{g}_i$  lower, so that the segments  $\mathbf{g}_i\mathbf{a}$  or  $\mathbf{g}_i\mathbf{b}$  resp. are nearly crossing the line  $\mathbf{cd}$ , we obtain non overlapping intervals  $\mathbf{t}_{a,i}\mathbf{t}_{b,i}$  and  $\mathbf{t}_{a,i+2}\mathbf{t}_{b,i+2}$ . So, we can achieve that except for the consecutive intervals  $\mathbf{t}_{a,j}\mathbf{t}_{b,j}$  and  $\mathbf{t}_{a,j+1}\mathbf{t}_{b,j+1}$  with  $j = 0, \dots, n - 6$ , no intervals overlap. Placing one Steiner point slightly above each overlap of the intervals gives the number of  $\lceil \frac{n-5}{2} \rceil$  interior Steiner points. One can decompose the polyhedron as described in the proof of Theorem 5. □

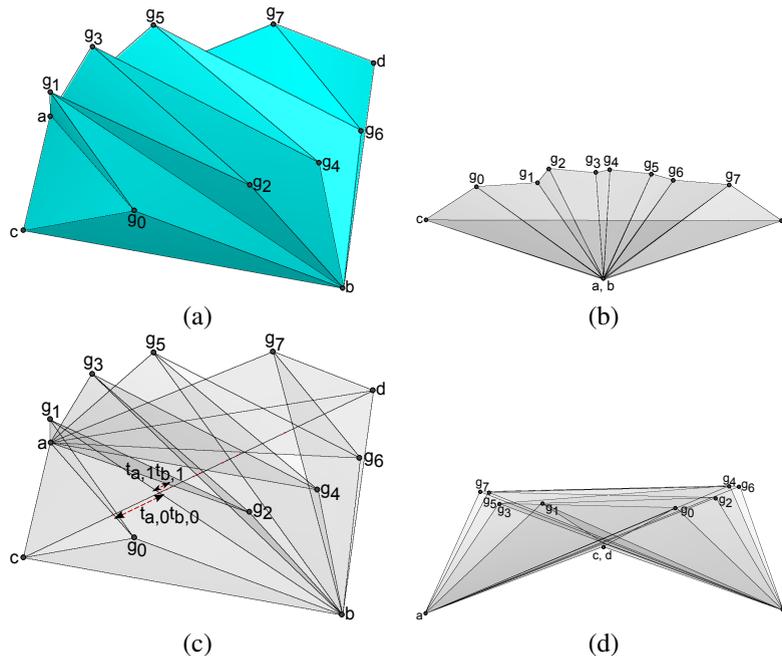


Fig. 11. An example polyhedron,  $\sigma_{12}$ , with 12 vertices. The coordinates of the vertices are given in the Table 4. Different views of this polyhedron are shown in (a), (b), (c), and (d), respectively. In particular, two overlapping intervals are shown in (c).

Figure 11 shows a particular example of such a polyhedron with 12 vertices. The coordinates of the 12 vertices is given in Table 4. By our construction, this polyhedron satisfies the property that only two adjacent intervals are overlapping. A pair of such intervals is illustrated in Figure 11 (c). Therefore, this polyhedron needs at least 4 Steiner points to be decomposed, which is optimal for this case.

	<b>a</b>	<b>b</b>	<b>c</b>	<b>d</b>	<b>g<sub>0</sub></b>	<b>g<sub>1</sub></b>	<b>g<sub>2</sub></b>	<b>g<sub>3</sub></b>
x	-1.294	4.830	4.830	-3.536	4.253	-0.301	3.117	-2.183
y	10	0	10	0	6.532	9.760	2.999	8.657
z	4.830	1.294	-1.294	3.536	-2.426	0	-2.571	0.646
	<b>g<sub>4</sub></b>	<b>g<sub>5</sub></b>	<b>g<sub>6</sub></b>	<b>g<sub>7</sub></b>				
x	1.874	-3.330	0.163	-4.051				
y	1.002	6.864	-0.105	3.184				
z	-1.808	1.350	-0.366	2.242				

Table 4. A choice of the coordinates of the vertices of a  $\sigma_{12}$ . The geometry of this polyhedron is shown in Figure 11. With these coordinates, this polyhedron needs at least 4 Steiner points to be decomposed.

#### 4. Discussion

We comment that our construction of a Steiner point in Bagemihl’s polyhedra as well as its generalizations is not unique. Note that the line segment  $B_1C_2$  in the Bagemihl’s polyhedron always touches the visible polyhedron. It is always possible to choose a Steiner point near this line segment such that it can decompose the polyhedron. The Steiner point can be chosen such that it is near the interval cut by the two planes containing the triangles  $A_1A_2C_1$  and  $A_1A_2B_2$  for  $\pi_6$  (or  $A_1A_2D_1$  and  $D_kA_2B_2$  for  $\pi_n$ , where  $n > 6$ ) and the line segment  $B_1C_2$ .

The Theorem 1 of Bagemihl proves the existence of a class of polyhedra (that satisfy all these properties). The following two open questions are interesting:

- (1) Except the generalized Bagemihl’s polyhedra  $\tilde{\pi}_n$ , is there other construction that satisfies Theorem 1.
- (2) Does every polyhedron satisfying the properties in Theorem 1 require only one Steiner point to be decomposed?

The result of Theorem 5 shows that any  $\sigma_7$  needs only one Steiner points to be decomposed, regardless of its geometry. However, we do not know whether this is true or false for an arbitrary 3d polyhedron with 7 vertices.

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#### References

- [1] Bagemihl, F. (1948). On indecomposable polyhedra. *The American Mathematical Monthly*, 55(7):411–413.
- [2] Below, A. (2002). *Complexity of Triangulation*. PhD thesis, Swiss Federal Institute of Technology, ETH Zürich. DISS. ETH No. 14672, 2002.
- [3] Chazelle, B. (1984). Convex partition of polyhedra: a lower bound and worst-case optimal algorithm. *SIAM Journal on Computing*, 13(3):488–507.
- [4] De Loera, J. A., Rambau, J., and Santos, F. (2010). *Triangulations, Structures for Algorithms and Applications*, volume 25 of *Algorithms and Computation in Mathematics*. Springer Verlag Berlin Heidelberg.
- [5] George, P., Borouchaki, H., and Saltel, E. (2003). Ultimate robustness in meshing an arbitrary polyhedron. *International Journal for Numerical Methods in Engineering*, 58:1061–1089.
- [6] George, P., Hecht, F., and Saltel, E. (1991). Automatic mesh generator with specified boundary. *Computer Methods in Applied Mechanics and Engineering*, 92:269–288.
- [7] Lennes, N. (1911). Theorems on the simple finite polygon and polyhedron. *American Journal of Mathematics*, 33(1/4):37–62.
- [8] Rambau, J. (2005). On a generalization of Schönhardt’s polyhedron. In Goodman, J. E., Pach, J., and Welzl, E., editors, *Combinatorial and Computational Geometry*, volume 52, pages 501–516. MSRI publications.
- [9] Ruppert, J. and Seidel, R. (1992). On the difficulty of triangulating three-dimensional nonconvex polyhedra. *Discrete & Computational Geometry*, 7:227–253.
- [10] Schönhardt, E. (1928). Über die Zerlegung von Dreieckspolyedern in Tetraeder. *Mathematische Annalen*, 98:309–312.
- [11] Si, H. (2015). TetGen, a Delaunay-based quality tetrahedral mesh generator. *ACM Trans. Math. Softw.*, 41(2):11:1–11:36.
- [12] Weatherill, N. P. and Hassan, O. (1994). Efficient three-dimensional Delaunay triangulation with automatic point creation and imposed boundary constraints. *International Journal for Numerical Methods in Engineering*, 37:2005–2039.