SPATIAL ANALYSIS OF FIRE HYDRANT PLACEMENT IN THE ENGINE ROOM USING THE VORONOI DIAGRAM

MAO TZE BAYOTAS
Maritime Academy of Asia and the Pacific, Bataan, Philippines
e-mail: maotze.bayotas@maap.edu.ph
Orcid: 0009-0005-4524-9699

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Keywords

Spatial analysis, fire hydrant, Voronoi diagram, Delaunay Triangulation

Abstract

Building new ships for navigation requires a proper layout of the different machinery and life-saving appliances. This should conform to the international standard set by the International Maritime Organization (IMO) to ensure the seaworthiness of the vessel and safety at sea. Fire hydrants and hoses are two of the most essential firefighting appliances installed onboard. In this study, the proper placement of the fire hydrants was determined using the Voronoi diagram. Considering the maximum length of the fire hoses in the engine room, as stated in the International Convention for the Safety of Life at Sea (SOLAS 1974), the critical points were plotted using a Cartesian Coordinate System drawn into scale. Distance formula and Voronoi diagram were applied to determine the optimal points for the least number of hydrants covering a much larger area. It was concluded that with different dimensions and orientations of the deck, different placements of the hydrants could be generated. Regardless, the Delaunay Triangulation will always prove the optimum distance between hydrants. This study is of great significance in optimizing the ship design without compromising safety as the shipping industry moves towards a green revolution while adopting the mantra of efficiency.

1 INTRODUCTION

The shipping industry continues to grow exponentially due to the rising demands in trade of nations worldwide. Despite the impact of the pandemic, the world commercial fleet increased by 63 million deadweights from 2020 to 2021 (UNCTAD, 2022). Safe voyage is essential to ensure the successful transport of cargo, and this is the primary concern of the International Maritime Organization. The International Maritime Organization (IMO) requires all vessels sailing on international and domestic waters to have an operational and complete set of safety appliances, such as the fire hydrant (IMO, 2020). Fire hydrants are very important since they are used for firefighting and general services, such as cleaning the holds. Currently, no mathematical models are used by naval architects in the design and placement of hydrants.

Several shipboard fires were reported in the past years, and 99 vessels of 100 gross tonnages or more were lost in the last ten years (Allianz Global Corporate and Specialty, 2021). Thousands of lives of seafarers were also lost due to fire. In 2020, the European Maritime Safety Agency (EMSA) reported that 15% of the incidents from

2014 to 2019 were caused by a fire in the engine room (EMSA, 2022). Architects and engineers widely conduct spatial analysis using Voronoi diagrams to maximize space. There are different spatial analysis methods for different purposes and configurations, but the Voronoi Diagram is specialized for determining points for maximum coverage (Gahegan, Lee, 2011).

This study formulated a general equation for placing the fire hydrants on different floor configurations using the Cartesian Coordinate System and Voronoi Diagram. This will lead to the maximization of the floor area using the least possible number of fire hydrants, which will increase the safety and efficiency of engine room operations while reducing the cost of vessel construction. The general equation only covers the location of the fire hydrants on a flat surface in the engine room and does not consider the materials used in the construction of the hydrant.

This study aims to formulate a general equation using spatial analysis and the Voronoi Diagram for the maximization of the placement of fire hydrants in the engine room. To attain such an objective, the following questions need to be addressed:

- What are the stipulated regulations when it comes to the installation of fire hydrants and fire hoses onboard ships, especially in ship design?
- How can the Voronoi Diagram be used in the determination of the installation points of the fire hydrant in a representative floor plan of an engine room?
- How is the spatial analysis method, specifically Delaunay Triangulation, used in the verification of the installation points determined by the Voronoi Diagram?
- How can a general equation be derived in the determination of the installation points of the fire hydrant, ensuring maximization of the floor area without compromising safety?
- What is the verification process in the confirmation of the validity of the determined installation points for a particular configuration of a floor area?

2 METHODOLOGIES

The research methodology employs a quantitative approach using mathematical methods, specifically the Voronoi Diagram and spatial analysis methods. To derive the general equation, the standard dimension of fire hydrants, as stated in SOLAS, was considered along with a representative dimension and orientation of an engine room floor plan. Quantitative analysis is then performed and divided into two stages: first is the implication of the Cartesian Coordinate System with the application of calculus, and second is the application of the Voronoi Diagram (De Berg and others, 2000). A median area of the commonly used dimensions onboard and the Voronoi Diagram constituted the spatial analysis method. Important provisions stated in SOLAS, as well as the minimum dimensions set by the International Association of Shipbuilders (IAS), were considered. The derivation of the equation started with the determination of a representative dimension of the commonly used configuration of floor plans used in the construction of vessels above 500 gross tonnages. The representative floor area was set as a rectangle due to its trigonometric and geometric properties and scalability. The dimension of the representative floor area was set to 30 m × 40 m. This was then scaled into a Cartesian coordinate plane with a 1 m: 1 unit scale measurement. Subsequently, the number of circles with identical radii, representing the length of the fire hose, which was the maximum length, is determined using calculus. The centers of the circles are determined using the equation:

$$(x-a)^2 + y - b^2 = r^2$$

where:
x = x-coordinate of the center of the circle
y = y-coordinate of the center of the circle
r = radius of the circle

Once the centers of the circle were determined, the maximum distance between circles was determined using the maximum neighbor formula, which is commonly used in geospatial analysis:

$$E(d_1) = 0.5 \sqrt{\frac{A}{N}} + (0.0514 + \frac{0.041}{\sqrt{N}} x \frac{B}{N}$$

where:

A = area of the plane
B = perimeter of the plane
N = number of critical points

The resultant distances are the direct distances, which are the shortest possible distances between centers. The critical points were established along with the positioning of these points using the Voronoi Diagram. The critical cells were drawn around each point, which represents the coverage of each fire hydrant and its critical boundaries. The Voronoi Diagram mathematically determined the optimal distances between the critical points, covering the floor area with the least number of fire hydrants at strategic positions for safety and economy. The distance formula was used in determining the distances between the critical points. The relationship and distance between the points are geometrically analyzed using the slope-intercept equation of the straight lines connecting each point. The derived equation will then be validated by applying it to a floor plan with different orientations and dimensions.

3 RESULTS AND DISCUSSION

3.1 Application of Voronoi diagram on ship’s design

Currently, the application of the Voronoi diagram in ship design and spatial analysis for ship construction is not evident. The Voronoi diagram is commonly used in spatial analysis using computer algorithms applied in planar areas (Vinh, Barolli, 2016). Voronoi diagrams are also used hand in hand with computer engineering in designing interactive spatial designs based on changing parameters. The most remarkable application of such is in telecommunication, wherein it was used to determine the optimal placement of signal towers (Gaj and others, 2019).

Thus, this is the first application of the Voronoi Diagram in ship design and construction, specifically to the placement of fire hydrants. With the sample floor area dimensions along with the scaling measurement, the Cartesian coordinate system was laid out. The first quadrant was utilized to deal with positive integers only in the subsequent calculations. The center points were determined with consideration of the smallest deviation possible. The formula for the determination of the number of center points is:

$$C = \left(\frac{A}{P}\right) x\ 7/4$$

where:

A= area of the floor plan
P= perimeter of the floor plan
C= number of center points

The ratio of 7/4 was derived from the table of the different polygons used in the convex-hull algorithm (Barber and others, 1996). Based on the formula given above, the number of certain points is 15. The 15 center points are labeled X1, X2… X15 and are distributed using the principle of Delaunay triangulation throughout the Cartesian coordinate system. The center coordinates were then derived using the ranges of the x and y coordinates of each division.

$$\left[A_x\ A_y\ B_x\ B_y\ \ A_x^2 + A_y^2\ 1\ B_x^2 + B_y^2\ 1\ \ C_x\ C_y\ D_x\ D_y\ \ C_x^2 + C_y^2\ 1\ D_x^2 + D_y^2\ 1\ \right] = \left[A_x - D_x\ A_y - D_y\ (A_x^2 - D_x^2) + (A_y^2 - D_y^2)\ \ B_x - D_x\ C_x - D_x\ \ B_y - D_y\ C_y - D_y\ \ (B_x^2 - D_x^2) + (B_y^2 - D_y^2)\ (C_x^2 - D_x^2) + (C_y^2 - D_y^2)\ \right] > 0$$

Where:

A= x and y coordinates of the top left point in the cell
B= x and y coordinates of the bottom left point in the cell

C= x and y coordinates of the top right point
D= x and y coordinates of the bottom right point

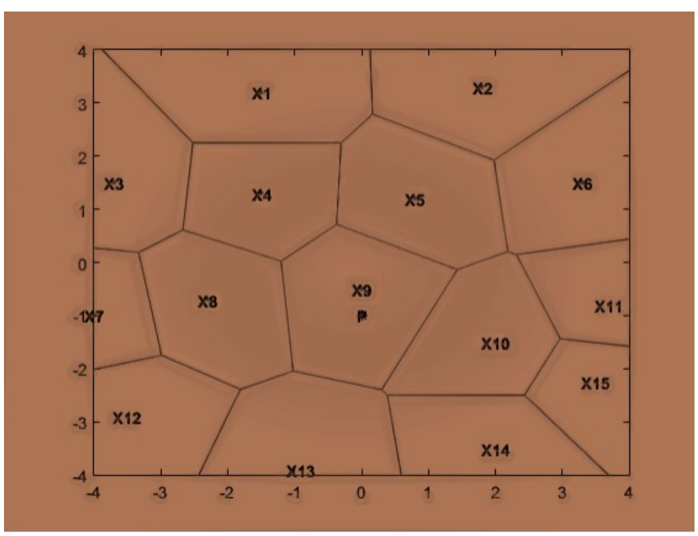
The number of divisions that the plane should be divided can be determined by C +1 (Aurenhammer, Klein, 2000). The center coordinates of each cell are provided below.

Division	Boundary Coordinates	Center Coordinates
1	(0,30) (0,22.5) (10,22.5) (10,30)	(13,30)
2	(10,30) (10,22.5) (20,22.5) (20,30)	(30,30)
3	(20,30) (20,22.5) (30,22.5) (30,30)	(38,23)
4	(30,30) (30,22.5) (40,30) (40,22.5)	(25,22)
5	(0,22.5) (0,15) (10,22.5) (10,15)	(2,23)
6	(10,22.5) (10,15) (20,22.5) (20,15)	(12,22)
7	(20,22.5) (20,15) (30,22.5) (30,15)	(25,22)
8	(30,22.5) (30,15) (40,22.5) (40,15)	(40,13)
9	(0,15) (0,7.5) (10,15) (10,7.5)	(0,12)
10	(10,15) (10,7.5) (20,15) (20,7.5)	(9,14)
11	(20,15) (20,7.5) (30,15) (30,7.5)	(21,15)
12	(30,15) (30,7.5) (40,15) (40,7.5)	(31,10)
13	(0,7.5) (0,0) (10,7.5) (10,0)	(1,4)
14	(10,7.5) (10,0) (20,7.5) (20,0)	(16,0)
15	(20,7.5) (20,0) (30,7.5) (30,0)	(31,2)
16	(30,7.5) (30,0) (40,7.5) (40,0)	N/A

Table 1 The center coordinates for each cell created in the Voronoi plane.

Figure 1 below shows the generated Voronoi cells from the center points determined and the number of divisions calculated. This shows the placement of the hydrant in the representative floor area with their respective boundary cells.

Fig. 1 Generated Voronoi cells based on the 15 center points. Source: Author



4.2 Method of fire hydrant placement onboard ship

Determination of fire hydrant placement onboard is done once the important machinery and ship structure are already in place. The hydrants are then placed in such a way that they comply with the regulation set forth by the International Convention for the Safety of Life at Sea and other pertinent regulations. The main objective is to ensure that all parts of the vessel, especially in enclosed spaces, can be reached by the stream of water from the fire hoses (IMO, 2020). This trend of hydrant placement is based on the provisions of SOLAS along with the maximum reaching radius of the fire hoses. However, this placement can be done mathematically by the integration of the Delaunay triangulation together with the derivation of the line equation between the points. Delaunay triangulation was used in the creation of the Voronoi cells by connecting the central points to each other in a straight line, making sure that no two lines intersect with one another, forming a triangle which has three of the central points as their vertices as shown in Figure 2 (Arkfen, Weber, 2013).

Fig. 2 Delaunay triangulation in the formation of cell boundaries. Source: Author

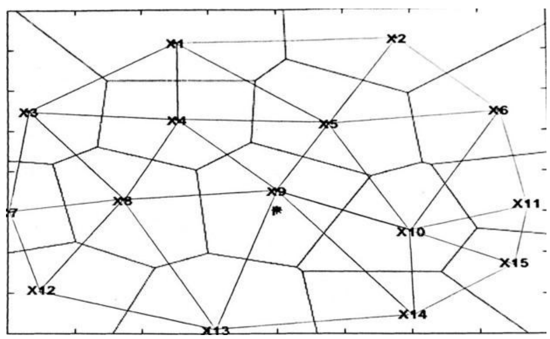
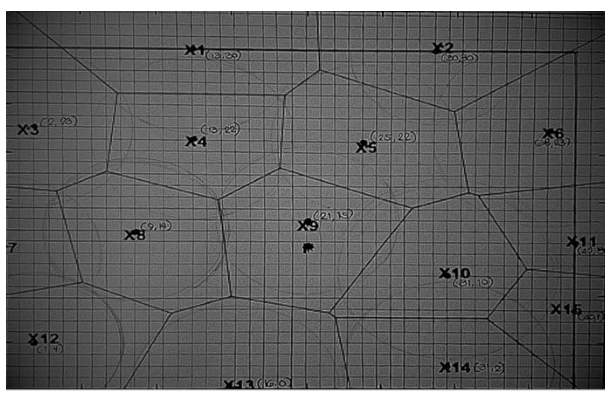


Fig. 3 Circular limits radiating from each center point. Source: Author



The intersections of the segments dividing the coordinates into 15 divisions and the side of the Delaunay triangle will become the vertices of the polygon enclosing the center point. Circles with a radius equal to the maximum length of the fire hoses have been drawn around each center point. The central points with the greatest number of circles intersecting them, regardless of the length of the arc, determine the terminal points to be included, as shown in Figure 3. The terminal points that are viable are X8, X5, and X10. The distances between the points were calculated using the distance formula. The distance of X8-X5 is 17.8885cm, the X8-X10 is 22.6607cm, and X10-X5 is 13.4164cm. For the generalization of the equation, which can be applied to other floor plans, the slope of the connecting lines was determined by the slope equation together with the ratio factor to other floor areas with different dimensions. The slope of the X8-X5 is 0.5, X8-X10 is -0.2, and X5-X10 is -2.0. Using the convex-hull algorithm equation for Voronoi Diagram, we determined the general formula for the minimum spatial distance between each center point in a specified floor area:

$$U = \frac{L\ x\ W}{B\ x\ C}\ x\ Y\ x\ Z$$

Where:

L= length of the floor plane
W= width of the floor plane
B= number of central points
C= number of cells
Y= Voronoi ratio (based on the table of the Voronoi ratio-demographic area)
Z= Delaunay constant for convex hull algorithm (from the Delaunay constant)
U= Distance minima

The slopes between the terminal points and the area are critical in the determination of the Voronoi ratio and the Delaunay constant from their respective tables. Using the Voronoi ratio shown in Table 2, the constant for a 40m x 30m parallelogram plane is 1.3, and the Delaunay constant is 2 by matching up the three slopes with reference to Table 3. The general formula is also very important in checking if the terminal points determined are correct. In this representative floor area, the distance minima is 13, which is less than the minimum spatial distance between the three terminal points, which is 13.4164. The method is the same when applying to a floor area greater or lesser than 1200 m^2. The convex hull-algorithm equation is very critical to confirm the accuracy of the determined terminal points, and the Voronoi diagram will automatically result in the least number of terminal points needed to cover the whole area of the demographic plane to be analyzed.

	31	31	33	34	35	36	37	38	39	40	41	42	43	44
22	2.1	0.9	0.3	1.2	4.1	5.5	6.2	0.1	1.3	4.2	9.8	9.0	7.2	6.1
23	3.9	4.8	6.3	7.4	10	2.3	3.4	6.6	7.5	7.9	2.2	0.4	6.8	8.6
24	4.1	4.3	3.5	6.0	5.8	5.9	9.6	9.7	2.8	0.2	4.3	5.9	6.8	7.0
25	7.3	3.5	4.6	6.8	7.8	3.7	4.7	9.8	9.9	0.8	1.6	2.8	3.7	8.5
26	1.1	2.4	3.5	4.6	5.7	7.8	8.3	4.8	5.9	6.1	4.8	9.8	7.6	6.5
27	3.9	7.5	7.6	8.3	4.6	7.0	8.4	3.2	3.1	3.9	4.0	5.0	4.8	9.7
28	3.7	7.4	8.4	6.9	8.9	6.5	7.6	2.3	3.4	5.6	3.2	4.5	6.8	8.8
29	1.2	1.0	0.6	0.8	8.6	5.4	5.5	7.5	6.4	8.2	9.3	9.4	5.7	8.5
30	1.0	3.5	6.7	8.4	4.9	6.9	3.0	3.1	1.4	1.3	6.5	3.9	7.9	7.5
31	2.3	4.6	6.7	8.7	9.8	3.5	6.4	5.3	3.2	4.8	8.8	7.6	5.8	9.0
32	1.9	2.0	3.4	4.6	7.6	3.4	5.4	7.8	8.9	9.3	3.4	4.6	4.7	4.8
33	1.2	0.8	6.7	7.4	5.8	9.8	3.2	1.1	0.1	4.3	4.2	5.4	6.5	6.9

Table 2 The center coordinates for each cell created in the Voronoi plane. Source: Held, 2005

	7.0	5.7	-0.2	8.4	9.0	6.0	1.6	8.5	
4.1	11.1	6.9	2.8	3.3	9.5	6.8	9.2	7.1	3.2
10.7	1.9	8.9	5.6	8.7	2.7	0.3	2.1	5.4	7.2
0.5	3.7	6.2	2.0	8.1	5.3	10.1	9.6	8.2	-2
5.2	0.2	10.4	8.3	0.7	4.6	2.7	3.8	0.9	6.1
3.1	7.9	1.1	3.6	5.1	3.9	9.1	4.7	9.4	8.0
2.4	6.4	4.4	7.5	2.9	5.9	0.1	6.3	1.2	4.2
4.3	0.6	4.0	2.2	1.4	4.9	7.4	4.8	5.0	2.5

Table 3 Tri-cross table for Delaunay constant value with three terminal points. Source: Skiena, 2008

5 CONCLUSIONS

As a result of the study, the optimal placement of the fire hydrants is affected by the floor area and the deck orientation. A mathematical equation was derived to determine the minimum distance between points. To ensure an optimal, effective, and accurate placement of the points, the Voronoi diagram is used along with the Cartesian Plane and the Delaunay Triangulation. The number of fire hydrants that should be placed on a given floor area will be determined by its perimeter and area. This will also dictate the number of Voronoi cells and the Delaunay triangles that would be deployed throughout the floor area. The range of each center point will trim down the possible center points into more optimal ones with the use of the convex-hull configuration. This will make the number of fire hydrants vary as the floor area increases; generally, the relationship between the two is directly proportional. The equation that is used for checking the minimum distance that should be maintained between fire hydrants is given by:

$$\frac{L\ x\ W}{B\ x\ C}\ x\ Y\ x\ Z = U$$

The fastest and most accurate method of plotting the Voronoi cells is through the help of the Cartesian Coordinates for accurate scaling and measurement, the Delaunay Triangle for the optimal position of central points, and finally, the convex-hull algorithm for the determination of the terminal points. Each configuration of floor area will have its corresponding plotting arrangement of Voronoi cells, and the constants used will change based on the tables, thereby affecting the placement of the central and terminal points.

It is recommended to apply further the Voronoi diagram method with the help of the Delaunay Triangulation, even to the accommodation area and the main decks, to extend the application of such. It is also recommended to explore the derivation of the general formula to be used for the determination of the optimum distances of points regardless of dimensions, but it is limited to those that are geometrically proportional. For safety purposes, the minimum number of fire hydrants can be set to a minimum value depending on the preference of the shipowner for the purpose of safety.

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