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The Mathematical Model to Compute the Quantity of 10cm Diameter Vertical Eucalyptus Posts Used for Formwork Preparation in Domes Construction

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Abstract The purpose of this study was to develop a mathematical model that helps to determine the quantity and heights of vertical eucalyptus posts used for formwork preparation in the construction of Orthodox Church domes. To achieve this, three steps are followed. In the first step, the shapes of the domes and the past experience were used to determine the quantity and heights of the vertical eucalyptus posts identified through structured interview conducted on experienced professionals selected based on purposive sampling technique. As a result, it has been realized that semi-spherical and parabolic shapes are common in Orthodox Church domes in the study areas and AutoCAD application is common to determine the quantity and heights of the vertical eucalyptus posts. In the second step, mathematical model is developed to determine the quantity and heights of vertical eucalyptus posts based on the results obtained from interview questions. In the third step, comparisons are conducted between the developed model and past experience to verify the effectiveness of the developed model. The result revels that there is almost no difference between the newly developed mathematical model and the past experience, and realized that the newly developed model is helpful in determining the quantity and heights of the vertical eucalyptus posts within short period of time and greater accuracy. It is advised that stakeholders engaged on projects including dome construction can use this newly developed model to improve their efficiency and accuracy.

Keywords Eucalyptus Quantity, Dome, Mathematical-Model, Construction Formwork

1. Introduction

Although dome construction has a long history, it is true that the beginning of concrete dome construction came with the discovery of cement. Concrete domes have many advantages, among which are to cover pre stressed concrete tanks [1, 2], to cover roofs with long span length without intermediate support [3, 4], to build a nuclear containment structure to prevent radioactive elements from escaping [5], and to indicate religious symbolism [6]. Different studies indicate that these concrete domes have various complex shapes related to the culture of the society and religion. To cite some of the studies, Tong and Rotters [4] noted that the concrete domes used to cover long-span roofs were conical, spherical, or elliptical in shape. The study conducted by Reyhan [7] also showed that the dome that was used to cover the Ottoman bath was spherical in shape. In addition, in the study conducted by Kobielak and Zamiar [8], the dome shape that was primarily used as a cover for long-span roofs was oval. So, formwork plays a major role in providing the desired shape. However, the traditional formworks used to give the desired shapes to concrete domes are costly [9]. Although various studies have been conducted to reduce this cost, in countries such as Ethiopia, there are limitations in terms of identifying dome shapes and developing a mathematical model that can calculate the height and number of wooden vertical members that support the formwork. In the Ethiopian Orthodox Tewahedo Church, the widely used vertical support during the preparation of the dome construction formwork is the eucalyptus. Figure 1 below shows a wooden formwork made up of vertical eucalyptus posts to support the fresh filling concrete of semi-spherical dome shaped Church project under construction in Ethiopia black water town.

Figure 1. Eucalyptus vertical posts to prepare hemispherical dome formwork for St. Mary church under construction in Tikur Wuha town, Oromia, (Ethiopia)

The main objective of this study is to develop a mathematical model that helps to determine the number and heights of the vertical eucalyptus supports which are widely used during the preparation of the dome construction formwork in Ethiopian Orthodox church construction projects and to validate through a sample study.

1.1. The General Objective of the Study

To develop a mathematical model that can help to quantify the total number and heights of eucalyptus vertical supports in the construction of Orthodox Church domes formwork.

1.1.1. Specific objectives

- ✓ To identify the shapes of domes in Orthodox Church buildings
- ✓ To review past experiences in dome formwork preparation
- ✓ To develop mathematical model and validate through sample study

2. Concrete and its Formwork

In particular, the role of formwork is significant during the construction of concrete buildings [10]. It helps in determining construction activities duration and schedule [11], and creates an opportunity to complete construction with quality [12]. However, if the right type of formwork is not chosen in the right place and installed carefully, it can lead to high cost and risks [13, 14]. With this in mind, various studies have been conducted to help improve the cost and efficiency of the formwork. In the study conducted by Thomsont et al.[15], it has been identified that the cost of the formwork obtained from proprietary is better than prepared on-site. Similarly, Taylor et al. [16] indicated that the traditional formwork system is prone to waste and costly, and they developed a lean formwork construction model and realized that it has good efficiency. On the other hand, in a study conducted by Arslan and Suba [17], they showed that traditional formwork with watered surface is weak in terms of resisting concrete pressure. In their study, R.K.M and S.H.M [18] realized that traditional formwork system is not viable for high-rise buildings in terms of cost, quality, and time, and pointed out that climbing formwork system has better efficiency. Similarly, Kim et al. [19] realized that traditional formwork system is not viable in their research on high-rise buildings and introduced a modified table formwork system. As can be understood from the articles used as references in this study, there is a gap in relation to formwork preparation in the case of developing a mathematical model to help determine the number and heights of vertical supports in relation to the preparation of dome construction formwork. The main objective of this study was to fill this gap.

3. The Research Methodology

3.1. Sample size and Sampling Technique

Purposive sampling technique is appropriate if there is information that the researcher wants to know in a particular situation and there are those who have the knowledge or experience to give the answer [20, 21]. In this study, it was considered to identify the shape and formwork preparation experience of the domes of the Orthodox Church under construction in Addis Ababa City and Oromia Regional State. With this in mind, five architectural engineers and three site engineers with high experience in the design and construction of church projects were identified using the purposive sampling technique.

3.2. Questionnaire Design

A 30 - 60min structured interview is an appropriate type in situations where a written questionnaire is not believed to be satisfactory in terms of the level of knowledge of the respondents and if the researcher is looking for a specific response [22]. In this study, five experienced architectural engineers each for 30min and three construction engineers each for 40min were exposed to structured interview to identify the dome shape and formwork preparation experience of the church construction projects that were built in Addis Ababa City and Oromia Regional State. The information given in table 1 indicates the designation of respondents, their work experience, and roles in their position.

Table 1. Background of respondents and interview period

No	Designation	Work experience	Role	Interview duration
1	Architectural Engineer	16 years	Designing and consulting	30min
2	Architectural Engineer	19 years	Designing and consulting	30min
3	Architectural Engineer	22 years	Designing and consulting	30min
4	Architectural Engineer	27 years	Designing and consulting	30min
5	Architectural Engineer	32 years	Designing and consulting	30min
6	Site Engineer	21years	Carrying out the construction work	40min
7	Site Engineer	25 years	Carrying out the construction work	40min
8	Site Engineer	30 years	Carrying out the construction work	40min

3.3. Analysis of Data

Using the structured interview, it was able to identify the shapes of church domes that were being built in the places where the study was conducted and the experiences in preparation of formwork used to build the domes. A mathematical model was developed to calculate the height and total number of eucalyptus vertical posts used for the preparation of formwork based on the results of the interview shown in Table 2 below, and the comparison of the outputs was carried out using the result generated from developed model and past experiences, and described in Table 3.

Table 2. Responses on the shapes of church domes under construction in Addis Ababa and Oromia Regional State and experience to determine the height and total number of vertical posts in formwork preparation

Responses on Shapes of Domes						
Designation	1	2	3	Remark		
Architectural Engineer1	Hemi-sphere	Parabolic	_			
Architectural Engineer2	>>	>>	_			
Architectural Engineer3	>>	>>	_			
Architectural Engineer4	>>	>>	_			
Architectural Engineer5	Hemi-sphere	Parabolic	Conidial			
Past experience on dome construction						
Designation	The Application type used	The interval between the vertical posts	The diameter of the vertical posts	Average height of 10cm dia. Eucalyptus posts	Height determination technique	Number of posts determination technique
Construction Engineer1	Auto CAD	60cm	Ø10cm	3m	Extending vertical lines from base L to the curve and measuring the height using Auto CAD	Drawing the base of the dome with Auto CAD, extending straight lines in two directions perpendicular to each other and counting the number of intersecting points in and on the base
Construction Engineer2	Auto CAD	60 or 80cm	Ø10cm	3m	>>	>>
Construction Engineer3	Auto CAD	60cm	Ø10cm	3m	>>	>>

Table 3. Determination of the number of eucalyptus vertical posts for parabolic and semi-spherical domes

Shape of the dome	Diameter (L)	Total number of vertical eucalyptus posts using developed model $n_C = \frac{\pi}{4}\left(\frac{L}{S}\right)^2$ (a)	Total number of vertical eucalyptus posts Through counting intersection points of CAD output (b)	Diff. (a–b)	Elevation from the level ground to the base of the dome (y)	Elevation from the base of the dome to the maximum height of the dome	Number of intervals between posts	The total length of vertical eucalyptus posts using eq. (15) and (24) respectively	The average length of 10cm diameter vertical eucalyptus posts	The total number of vertical eucalyptus posts using eq. (16) and (25)
Parabolic	3.6m	28.3 = 29	29	0	9m	2.5m	5	286.3m	3.5m	82 piece
Semi-spherical	6m	78.5 = 79	78	1	7.8m	3m	9	810m	3.5m	232 piece

According to the results shown in table 2 below, the responses obtained from the five architectural engineers selected as a sample show that the dome shapes under construction in the areas where this study was conducted are mostly semi-spherical and parabolic. On the other hand, in an interview to identify the experiences related to dome construction, the responses obtained from 3 respondents selected as a sample showed that the application being used is Auto CAD; the interval between vertical eucalyptus posts is 60cm; the average diameter of eucalyptus post is 10cm; the average height of 10 cm diameter eucalyptus is 3m, and the Auto CAD application is used to calculate the quantity and heights of the vertical posts.

3.4. Developing a Mathematical Model to Calculate the Quantity and Total Length of Vertical Eucalyptus Posts

To develop a model that helps to calculate the quantity and total length of vertical eucalyptus posts used for the preparation of dome formwork, two sections are taken into consideration. The first section is from the level of the ground surface to the base of the dome and the second one is from the base of the dome to its maximum elevation.

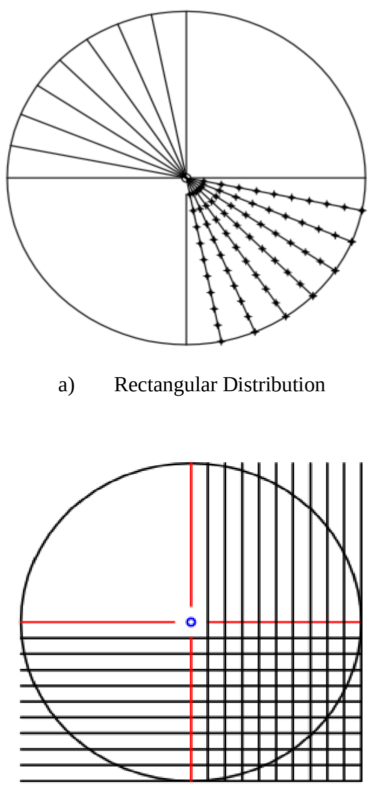
i. For the section from the level ground to the base of the dome

In the first part, from the level ground to the bases of the domes, all the vertical eucalyptus posts are of equal heights, and if their quantity is known, the required length of the vertical eucalyptus posts can be easily found.

Considerations

- ✓ The domes considered for this study are parabolic and semi-sphere.
- ✓ The bases of the domes are circular.

To determine the total number of vertical eucalyptus posts both the rectangular and radial distribution of the vertical posts as shown below in figure 2a and 2b respectively has been tested. For the ease of constructability, the rectangular distribution has been taken into consideration.



a) Rectangular Distribution

b) Radial Distribution

Figure 2. Rectangular and Radial distribution of vertical posts

Due to the fact that the bases of the different domes considered in this study are circular, the following assumption has been made to develop a formula for determining the total number of the vertical eucalyptus posts.

Assumption

- ➢ The ratio of the area of the rectangle to the area of the circular base and the ratio of the total number of vertical posts in the rectangle to the total number of posts in the circle are proportional to each other.

Mathematically this can be expressed as:

$$\frac{A_R}{A_C} = \frac{n_R}{n_C} \quad (1)$$

Where, A_R = the area the rectangle, A_C = the area of the circle, n_R = the number of vertical posts in the rectangle, and n_C = the number of vertical posts in the circle.

Since the diameter and/or the sides of the rectangle is L,

$$\frac{L^2}{\left(\frac{\pi L^2}{4}\right)} = \frac{n^2}{n_C},\ \boldsymbol{n_C = \frac{\pi}{4} n^2} \quad (2)$$

Since there are a number of vertical posts on the diameter of the circle and/or the sides of the rectangle, this implies the total number of vertical posts in the rectangle, $n_R = n * n = \boldsymbol{n^2}$ and as shown in the fig above, the diameter of the circle and/or the sides of the rectangle is **L** and the interval (the center to center distance between successive vertical post is **S**). The number of vertical posts along the diameter of the circle and/or the sides of the rectangle can be obtained,

$$n = \frac{L}{S} \quad (3)$$

Substituting equation (3) into equation (2),

$$n_C = \frac{\pi}{4}\left(\frac{L}{S}\right)^2 \quad (4)$$

Once the formula to calculate the total number of vertical eucalyptus posts has been developed, the total length of the vertical eucalyptus posts can be obtained using the equation:

$$L_{tot(sec-1)} = n_c * y = \frac{\pi}{4}\left(\frac{L}{S}\right)^2 * y \quad (5)$$

Where y is the elevation of the vertical eucalyptus post from the level ground to the base of the dome.

ii. From the bases of the dome to its maximum elevation

a) In the case of semi-spherical dome

Assumptions

- The section of the dome considered in this case is a semi-circle that opens downward as shown below.
- The number of the vertical eucalyptus posts obtained using the developed equation in the first section is extended through the chords formed by the rectangular distribution of the posts and each chord is separated by a fixed distance S perpendicular to the center of the circular base.
- The y-coordinate is the central axis that bisect the curves.
- The curve has a height h on the y - axis and a base length L on the x – axis
- The curve is symmetrical about the Y and the X axis
- The interval between the chords and the vertical posts is = S

As shown in figure 3 below, the semicircle indicates the section of semi-spherical dome; the vertical lines in the half part of the semicircle indicate the arrangement of the vertical eucalyptus posts in the dome, the symbols y1, y2, y3------ etc. indicate the heights of the vertical eucalyptus posts, and the letter **S** indicates the distance between the vertical posts.

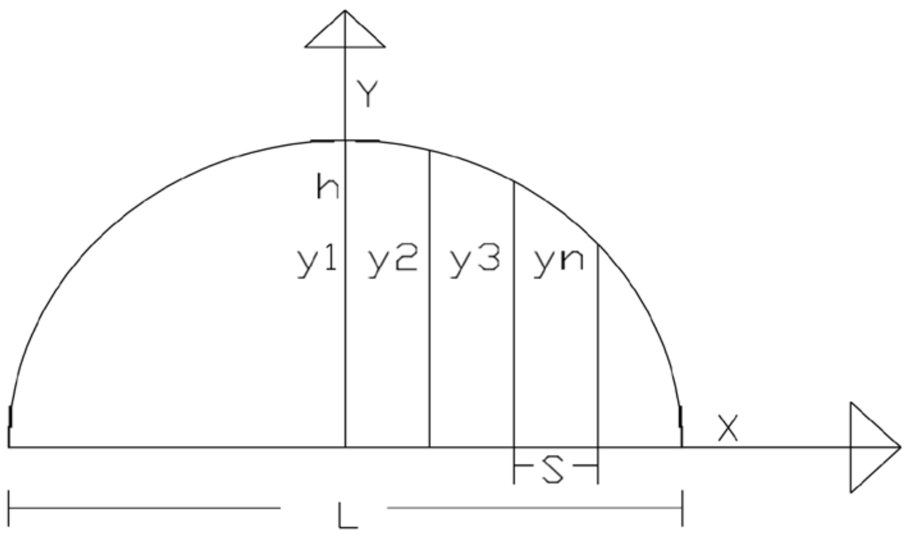


Figure 3. Section of hemi-spherical dome

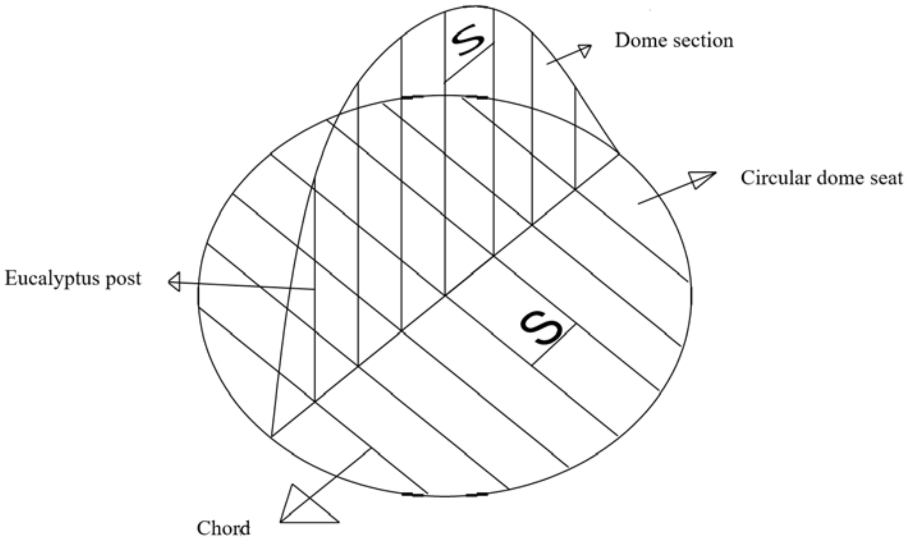


Figure 4. The circular base seat and the section of the dome

The parts described in figure 4 are the circular dome seat, the section of the dome, and the vertical eucalyptus posts. The horizontal circle indicates the dome seat; the vertical curve indicates the section of the dome, and the vertical lines inside the vertical curve indicate the eucalyptus vertical posts.

In the case of semi-spherical dome, the chord concept was used to determine the total number of the vertical eucalyptus posts and heights. For a chord perpendicular to the center of a circle, its length can be obtained using the formula [23],

$$l = 2 * \sqrt{(R^2 - S^2)} \quad (6)$$

Where l is the chord length, R is the radius of the circle, and S is the perpendicular distance from the center to the chord. But since there are n chords separated by a fixed distance S, equation (6) can be written in generalized form as:

$$l_n = 2 * \sqrt{(R^2 - (nS)^2)} \quad (7)$$

Where n = 0, 1, 2, 3,

If n = 0, the length of the chord and the diameter of the dome base becomes equal

$$\boldsymbol{number\ of\ chord} = \frac{\boldsymbol{The\ diameter\ of\ the\ circle}}{\boldsymbol{The\ interval\ between\ the\ chords}} = \frac{\boldsymbol{L}}{\boldsymbol{S}} - \mathbf{1}, \quad (8)$$

The total number of vertical eucalyptus posts on a given chord can be obtained by,

$$v_n = \frac{l_n}{S} = \frac{\sqrt{L^2 - 4(nS)^2}}{S} \quad (9)$$

Where v_n is the number of vertical eucalyptus posts on a given chord of length l_n,

And n is an index = ± 0, 1, 2, (10)

Here the plus and minus sign indicate the symmetry of the dome shapes.

In the case of semi-spherical dome, the height of each vertical eucalyptus posts can be considered as half of the length of each of the corresponding chords perpendicular to the circular base of the dome and separated by a distance S to each other. This implies the total length of the vertical posts from the base of the dome to its top that can be calculated by:

Y_{tot} = the summation of the product of the height of the vertical posts and the total number of the vertical posts on each chord.

Mathematically it can be expressed as:

$$Y_{tot} = \left(\sum_{i=\pm(n-1)/2} \frac{\sqrt{L^2 - 4(nS)^2}}{S}\right) * \frac{1}{2}\sqrt{L^2 - 4(nS)^2)}) \quad (11)$$

This implies,

$$Y_{tot} = \sum\left(\frac{L^2 - 4nS^2}{2S}\right) \quad (12)$$

But since the distribution of the vertical posts is symmetrical and except the diameter of the dome base (the largest chord), all the remaining chords are two in number in a given dome, and equation (12) can be simplified as,

$$Y_{tot} = \frac{L^2}{2S} + \sum_{i=-(n-1)/2}^{+(n-1)/2}\left(\frac{L^2 - 4(nS)^2}{2S}\right) \quad (13)$$

Where Y_{tot} is the total length of the vertical eucaluptus posts from the base of the dome to its top in the case of semi-spherical shape, $\frac{L^2}{2S}$ is the total length of the vertical posts on the diameter of the dome and $\sum_{n=\pm1}^{\pm n}\left(\frac{L^2 - 4(nS)^2}{2S}\right)$ is the total length of the chords different from the diameter of the dome base and the plus and minus sign indicate the symmetry of each chord to the right and the left of the diameter of the dome base.

But since the total length of the vertical posts is the total length from the level ground to the top of the dome,

$$\boldsymbol{D_{tot}} = \boldsymbol{L_{tot(sec-1)}} + \boldsymbol{Y_{tot}} \quad (14)$$

$$D_{tot} = \frac{\pi}{4}\left(\frac{L}{S}\right)^2 * y + \frac{L^2}{2S} + \sum_{i=-(n-1)/2}^{+(n-1)/2}\left(\frac{L^2 - 4(nS)^2}{2S}\right) \quad (15)$$

Where, D_{tot} is the total length of the vertical posts from the level ground to the top of the dome

Since we are interested to determine the total number of the vertical posts required to support the formwork,

$$P_{tot} = \frac{D_{tot}}{Average\ length\ of\ the\ posts} \quad (16)$$

Where, P_{tot} is the total number of the vertical posts from the level ground to the top of the dome

b) In the case of parabolic dome

Assumptions

- ➢ The section of the dome considered in this case is a parabola that opens downward as shown below.
- ➢ The number of the vertical eucalyptus posts obtained using the developed equation in the first section is extended through the chords formed on the circular base seat of the dome.
- ➢ The y-coordinate is the central axis that bisect the curves.
- ➢ The curves have a height h on the y - axis and a base length L on the x – axis.

As with a semi-spherical dome, the base seat of a parabolic dome is circular in shape. So that, like semi-spherical dome, the concept of chord can be used to determine the quantity of vertical eucalyptus posts. Following this, equation (7) and (8) can be used to determine the number of chords in the circular base and the total number of vertical eucalyptus posts on each chord respectively. The heights of the vertical eucalyptus posts from the base to the maximum elevation of the parabolic dome can be obtained using the developed model given below. As shown in figure 5 below, the parabola indicates the section of parabolic dome; the vertical lines in the half part of the parabola indicate the arrangement of the vertical eucalyptus posts in the dome; the symbols y1, y2, y3------ etc. indicate the heights of the vertical eucalyptus posts, and the letter **S** indicates the distance between the vertical posts.

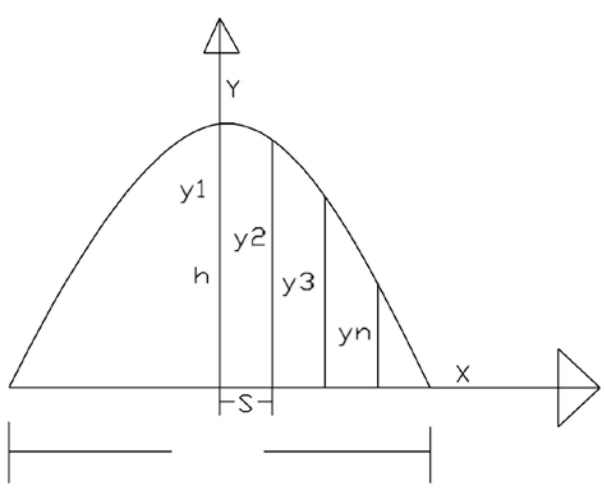


Figure 5. Section of parabolic dome

- ➢ The equation of a parabola that opens downward can be given by:

$$y = -a(x-p)^2 + k, or y = -ax^2 + bx + c \quad (17)$$

Where, (p, k) are the coordinates of turning points and a is a dilation factor.

Taking $y = -a(x-p)^2 + k$ and the values of the coordinates given in the fig. shown above,

$$using\ the\ coordinate\ (x,y) = \left(\frac{L}{2}, 0\right),$$

$$0 = -a\left(\frac{L}{2} - p\right)^2 + k$$

$$a = \frac{k}{\left(\frac{L}{2} - p\right)^2}$$

$$using\ the\ coordinate\ (p,k) = (0,h),$$

$$a = \frac{k}{\left(\frac{L}{2} - p\right)^2} = \frac{h}{\left(\frac{L}{2} - 0\right)^2}, \quad \boldsymbol{a = \frac{4h}{L^2}}$$

Therefore, the equation of the parabola can be written as,

$$\boldsymbol{y = -\frac{4h}{L^2}x^2 + h} \quad (18)$$

Let us consider the heights of the vertical posts supporting the fresh filling concrete and they are separated by a fixed interval s be $y_1, y_2, y_3 \ldots y_n$, as shown below,

The heights of the vertical posts can be obtained by:

$$\boldsymbol{y_1(x = S) = h - \frac{4h}{L^2}(S)^2},$$

$$\boldsymbol{y_2(x = 2S) = h - \frac{4h}{L^2}(2S)^2},$$

$$\boldsymbol{y_3(x = 3S) = h - \frac{4h}{L^2}(3S)^2} \ldots$$

$$\boldsymbol{y_n(x = nS) = h - \frac{4h}{L^2}(nS)^2} \quad (19)$$

For a parabolic dome, the total length of the vertical eucalyptus posts can be obtained by taking the summation of the product of the number of vertical eucalyptus posts on each chord and the height on each chord.

Mathematically this can be expressed as,

$$\boldsymbol{L_{tot} = \sum(v_n * y_n)} \quad (20)$$

But since, $\boldsymbol{v_n = \frac{\sqrt{L^2 - 4(nS)^2}}{S}}$, and $\boldsymbol{y_n = h - \frac{4h}{L^2}(nS)^2}$

$$\boldsymbol{L_{tot(sec-2)} = \sum_n \left(\frac{\sqrt{L^2 - 4(nS)^2}}{S}\right) * \left(h - \frac{4h}{L^2}(nS)^2\right)} \quad (21)$$

But since the distribution of the vertical posts are symmetrical and except the diameter of the dome base (the largest chord), all the remaining chords are two in number in a given dome, and equation (18) can be simplified as

$$L_{tot(sec-2)} = \frac{Lh}{S} + \sum_{i=-(n-1)/2}^{+(n-1)/2} \left(\frac{\sqrt{L^2 - 4(nS)^2}}{S}\right) * \left(h - \frac{4h}{L^2} * (nS)^2\right) \quad (22)$$

Where, $\frac{Lh}{S}$ is the total length of the posts on the diameter of the dome base

The total length of the vertical posts can be obtained by taking the length from the level ground to the dome base and from the dome base to its top

$$D_{tot} = L_{tot\,(sec-1)} + L_{tot\,(sec-2)} \quad (23)$$

$$D_{tot} = \frac{\pi}{4}\left(\frac{L}{S}\right)^2 * y + \frac{Lh}{S} + \sum_{i=-(n-1)/2}^{+(n-1)/2}\left(\frac{\sqrt{L^2-4(nS)^2}}{S}\right) * \left(h - \frac{4h}{L^2} * (nS)^2\right) \quad (24)$$

Where, D_{tot} is the total length of the vertical posts from the level ground to the top of the dome

Similar to the semi-spherical dome, we are interested to determine the total number of the vertical posts required to support the formwork,

$$P_{tot} = \frac{D_{tot}}{Average\ length\ of\ the\ posts} \quad (25)$$

Where, P_{tot} is the total number of the vertical posts from the level ground to the top of the dome

Where, L is the diameter of the dome base, Y is the elevation from ground level to the base of the dome, h is the elevation from dome base to its elevation, S is the interval between the posts and m is the average length of 10cm diameter vertical posts.

The algorithm given in figure 6 above indicates the prototype model developed to compute the eucalyptus quantity in the case of semi–spherical and parabolic domes formwork preparation.

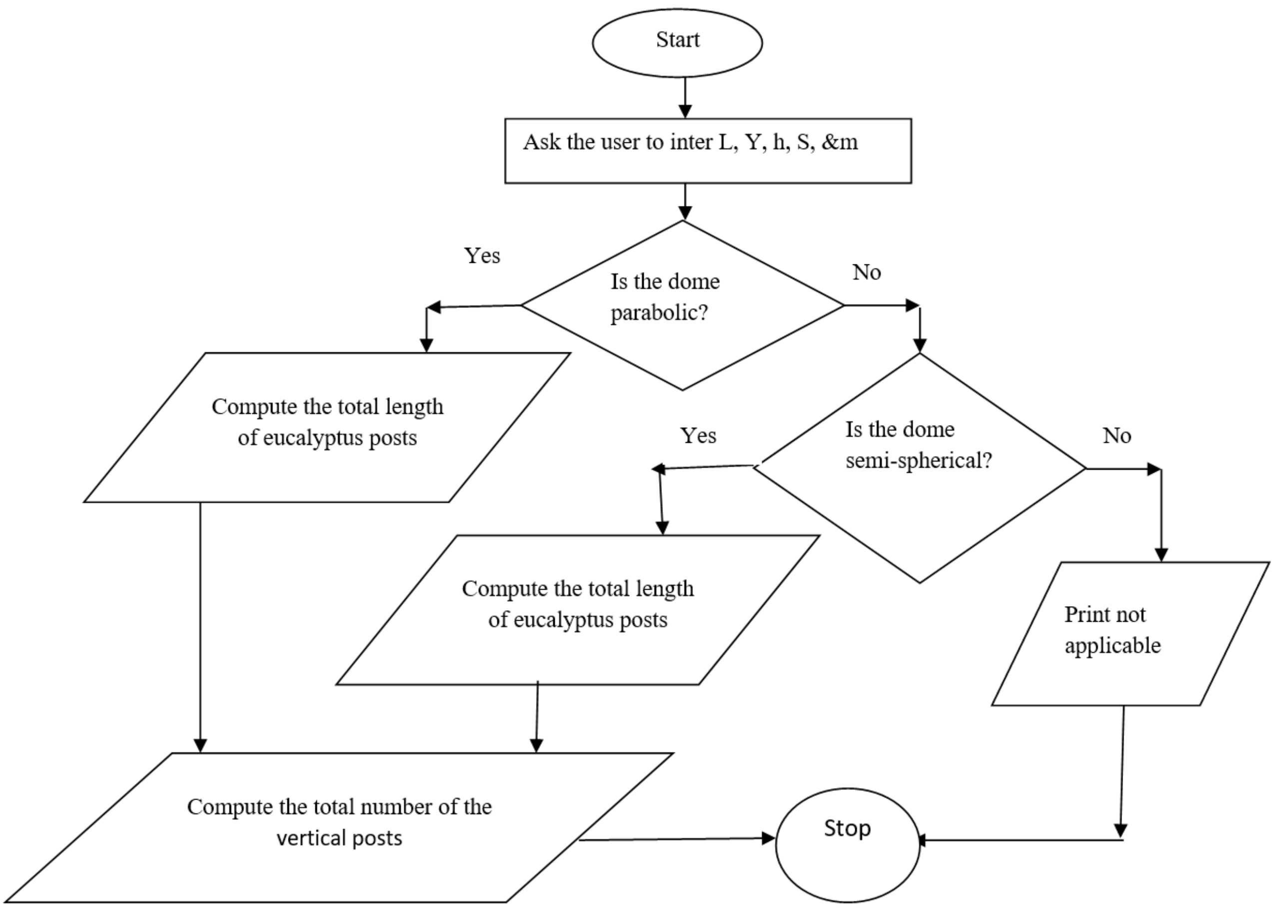
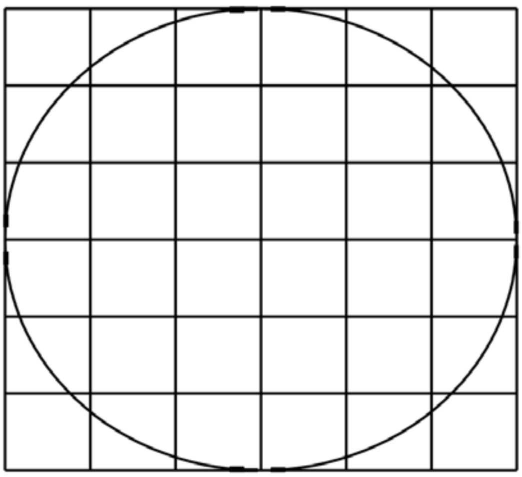


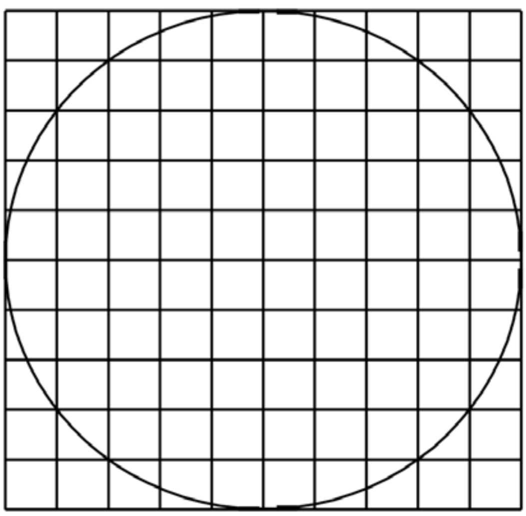
Figure 6. Algorithm to calculate the total number of vertical eucalyptus posts

4. Case Study

In this part of the study, one parabolic and one semi-spherical dome with diameter 3.6m and 6m respectively have been identified. The required number of 10cm vertical eucalyptus posts are computed and compared using the newly developed model as shown in table 3 below and past experience or using AutoCAD application as given in figure 7 below.



(a)



(b)

Figure 7. The number of intersecting lines generated from CAD (past experience) in the case of 3,6m diameter parabolic and 6m diameter semi-spherical domes respectively

5. Results and Discussion

The results described in table 3 show that the difference in the number of eucalyptus vertical posts obtained from the newly developed mathematical model and the past experience is negligible. As shown in table 3 of column 3 and 4 above, it indicates that the total number of eucalyptus vertical post points for a parabolic dome of base diameter 3.6m using the newly developed mathematical model and using CAD application (past experience) is 29. Similarly, as shown in table 3 of column 3 and 4 above, it indicates that the total number of eucalyptus vertical post points for a semi-spherical dome of base diameter 6m using the newly developed mathematical model is 79 and using CAD application (past experience) is 78. These results show that the difference in the quantity of eucalyptus vertical posts obtained from the newly developed mathematical model and the past experience is almost zero.

6. Conclusions

A mathematical model is developed to compute the total number of eucalyptus vertical posts that used to prepare formwork in the case of parabolic and semi-spherical domes construction. The shapes of the domes and determination of the total number of eucalyptus vertical posts in Orthodox Church buildings are obtained using key informant interview and the model is developed based on different assumptions. Finally, it has been realized that the developed mathematical model is helpful to determine the total number of vertical eucalyptus post that used to support the fresh filling concrete and give the desired structural shape.

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