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Design Optimization of a Lattice Tower: Structure and Foundations

Cossi Télesphore Nounangnonhou[1,2], Guy Clarence Semassou[1*], Kossoun Alain Tossa[1], Noémie Sintondji[1]

[1]Laboratory of Energetics and Applied Mechanics (LEMA), University of Abomey-Calavi, Abomey-Calavi, Benin
[2]Laboratory of Electrotechnics, Telecommunications and Applied Informatics (LETIA), University of Abomey-Calavi, Abomey-Calavi, Benin
Email: *nocteles2000@gmail.com

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Abstract

Produced in power plants, electrical energy is transported to places of consumption via the electricity network. At the heart of this network are the supports that allow electricity to be efficiently transported over long distances, guaranteeing the security and supply of energy to the various centers of use. In the construction of a line, supports occupy an important part in terms of safety and construction cost. It is therefore essential to optimize their use to reduce the cost of transmission lines. This work addresses this problem, which focuses on the optimal utilization of X-lattice towers in the construction of overhead power lines. The challenge is to reconcile the search for optimal cost and respect for the design, resistance and service constraints of the structure. To do this, a parameter having a strong correlation with the weight, foundation and construction cost of the X-lattice tower for 161 kV lines is determined as an important cost variable. This parameter is the wheelbase of the towers. The junction point between the structure and the foundations is obtained by measuring the forces at the base of the tower following the lowering of the loads. These efforts make it possible to size foundations which are of the inverted or isolated sole type. The results obtained reveal that from 8 meters in width, the wheelbase gradually changes until the optimum is obtained at 6.29 meters. With this wheelbase, the production cost is optimal. It clearly emerges from this study that the construction of lattice pylons with a wheelbase of approximately 6.29 meters makes it possible to optimize the cost of construction of 161 kV lines in the Republic of Benin.

Keywords

Lattice Tower, Wheelbase, Cost, Optimization, Foundation

1. Introduction

With rampant industrialization, the world's energy demand is constantly increasing and a country's energy consumption has become a barometer of its technological progress [1]. However, talking about energy also implies talking about electricity. In today's societies it is impossible to envisage daily life without electricity. The progress made since 2010 to guarantee access to electricity for all is notable. In 2017, the global electrification rate reached 89% compared to 83% in 2010. In Benin, this rate increased from 34% in 2010 to 73% in 2017 [2].

Faced with the problems of dilapidated and unstable transport networks on the one hand and saturation of distribution networks on the other, several projects aiming to improve and extend access to electricity have emerged in the Republic of Benin [3]. The most recent is the PADSBEE.

This 3-year project includes the construction of 1500 km of transmission lines and distribution networks, as well as 11 transformer substations [4]. The overall objective is to increase the national electrification rate to 75% by 2025 and to achieve good performance of the voltage plan at all nodes by 2025 [5]. However, in its alternative form, electricity cannot be stored [6]; its production must therefore adapt to the needs of consumers. Electricity must then be routed from production sites to consumption sites via electrical transmission lines. The lattice towers are essential links in this transport; they carry the electric cables. But these pylons are expensive works. Their cost is estimated between 35 and 45% of the total cost of an overhead power line [7].

In the PADSBEE, nearly a hundred million Euros will therefore be devoted solely to the pylons. The optimization of lattice towers in order to reduce their cost while guaranteeing their optimal service conditions is therefore a major concern of designers. Lattice towers are interesting structural optimization topics. The similarity of their configurations has the advantage that the results and experience obtained within the framework of one project can be generalized to other projects [8]. Depending on the chosen design variables, the structural optimization of lattice towers can be of 3 types: dimensional or size, geometric or shape and topological [9]. This type of construction therefore offers a lot of possibilities for optimization. It is for these reasons that several authors have studied the question.

Visweswara Rao [10] worked on the nonlinear optimization of a very high voltage (400 kV) electrical transmission pylon under several load cases. The control variables were the weight and the geometry of the pylon. As a result of the iterative calculations, a noticeable reduction in the weight of the structure is obtained when the width at the base (wheelbase) decreases. Conversely, when the wheelbase increases, the weight of the pylon also increases. S. Jovasevic *et al.* [11] as well as D. Zwick *et al.* [12] were interested in wind turbines. The former have developed a new design for hybrid onshore wind turbines consisting of a lattice part surmounted by a tubular part, while the latter have designed an offshore wind turbine whose entire height is lattice.

The objective of both works is to reduce the weight and cost of lattice structures through topological and dimensional optimization. It emerges from this work that an X-shaped triangulation of the lattices makes it possible to have a lighter but equally resistant structure. In their work on the structural optimization of electric transmission pylons [9], M. Khodzhaiev and U. Reuter used a new genetic algorithm with variable genome length and obtained a 10% reduction in the cost of the pylon by varying independently the number and height of the sections of a 110 kV pylon.

These various works demonstrate that although there are standards which govern the design of lattice towers on an international level, there are no standards as to the procedure for obtaining technical and economic optimality for a tower and its foundations [10]. We simply have design variables that we can modify to achieve a successful optimization. Thus, the work of these authors has the merit of highlighting the effect of the wheelbase on the weight of the pylon on the one hand, but also the choice of an X truss configuration making it possible to reduce both the weight and cost of the pylons. However, lattice towers are structures anchored in the ground (with foundations).

Seeking to optimize them cannot therefore be done without taking into account the interaction between the metal structure of the pylon and its foundations. Therefore, the footing of the pylon acts not only on the weight and cost of the metal structure, but also on the type, weight and cost of the foundations. These aspects are not addressed in the works consulted, yet they are of capital importance for the implementation of PADSBEE.

This article therefore aims to reconcile the mechanical aspects and those relating to the civil engineering of the construction of electricity pylons.

2. Materials and Methods

2.1. Materials

To carry out this work, data on the towers were collected from the Electric Community of Benin (CEB). This data concerns the height and cost of the lattice towers of the 161 kV lines, the wheelbase widths used, the loads induced by the lines and the type and cost of the foundations. The data obtained were used in the modeling of the towers using the TOWER software [13]. In addition, normative and indicative documents were used. Details of these are provided [14] [15] [16].

2.2. Methods

After a bibliographical synthesis, the X-truss lattice tower of a 161 kV electricity transmission line is sized in accordance with the CEB standards in force in the Republic of Benin. It is then modelled and checked in the TOWER software. Optimization of the pylon is finally carried out by varying the wheelbase. The approach followed to carry out this work is summarized in the flowchart in **Figure 1**.

- **Bibliographic synthesis**

Articles by various authors who have carried out work on the optimization of lattice towers are reviewed in order to make an inventory of the optimization paths explored, the methods used and the results obtained. Normative documents are also reviewed to highlight the design and dimensioning requirements that the structure must meet.

- **Pylon sizing**

The sizing of the pylon began with the survey of the geotechnical characteristics and the climatic conditions of the site where the pylon would be installed. This is the locality of Glo-Djigbé, a district of the commune of Abomey-Calavi, located in the Atlantique department, in Benin. This locality with geographical coordinates 6˚32'25" north, 2˚19'31" east, is located about 35 kilometers from the economic capital Cotonou. Based on the data recorded and the geometric, electrical and mechanical constraints on the line, the spatial layout and the overall dimensions of the pylon structure are determined; we then obtain the silhouette of the pylon. Then, the loads applied to the pylon due to service conditions and climatic action are evaluated for different load combinations. These loads as well as their points of application on the pylon, make it possible to draw up the different load trees of the pylon. The specifications followed for the sizing are presented in Table 1.

- **Modeling using TOWER software**

The silhouette of the pylon obtained above is modeled in the TOWER software. The different loads indicated by the load charts are then applied to the structure and then it is checked that the structure can withstand these forces without deforming. Modifications are made if necessary to obtain a valid structure. After the validation of this stage, one carries out the calculation of the

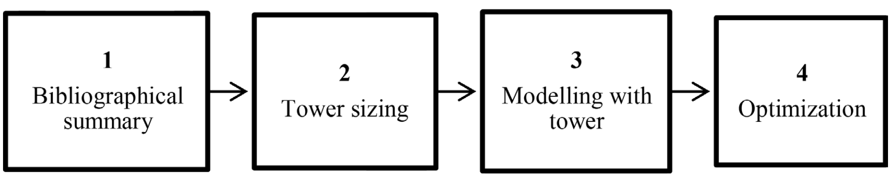

Figure 1. Working method.

Table 1. Requirements specification.

Implantation site	Soil type	Climatic constraints	Geometric and mechanical constraints	Constraints on the foundations
Glo-djigbé	Mixture of sand, silt and clay	Hypothesis A Temperature: 27˚C Wind: nil Hypothesis B Temperature: 27˚C Wind: 32 m/s Hypothesis C Temperature: 12˚C Wind: 19.2 m/s	Ground isolation distance: 8.5 m Ground wire protection angle: 25˚ Average range: 300 m Weight range: 600 m Wind range: 400 m	Anchorage depth: 2 to 3 m

structure. We then obtain the work rate of the various members, the weight of the metal structure as well as the forces exerted up to the feet of the structure. It is on this information that the dimensioning of the foundations is based.

- **Foundations sizing**

The values obtained in the TOWER software following the lowering of the loads and the geotechnical data of the soil are entered into a mini software coded in Excel. The foundation design is carried out by the software.

- **Optimization based on wheelbase variation**

The width at the base of the pylon (wheelbase) is retained as a design variable for optimization. Depending on the value of this parameter, changes are recorded both on the metal structure of the pylon and on its foundations. Indeed, if the wheelbase becomes larger or smaller, the metal structure becomes heavier or lighter, its resistance and its cost are then modified. The same is true for foundations. Depending on the value retained for the footing, the foundations receive more or less high efforts and their dimensions and costs also vary. It is therefore necessary to vary the value of the footing of the dimensioned pylon whose resistance has already been checked and the foundations dimensioned. The variation is made in the TOWER software. The principle followed for this variation is shown schematically in Figure 2.

To modify the wheelbase, the angle ***a*** of inclination of the feet of the pylon with respect to the vertical is modified, in doing so the distance ***x*** varies in order to maintain constant the height H under the lower console of the pylon. This principle was applied in the TOWER software used to model the pylon. The variation of the wheelbase in the software consisted in modifying several times the coordinates of the nodes modeling the feet of the structure. Starting from the design value (that of the dimensioned pylon), the wheelbase is modified according to a step of 50 cm. By evaluating the resistance of each structure obtained for the different values of the wheelbase, the range of possible variation of the

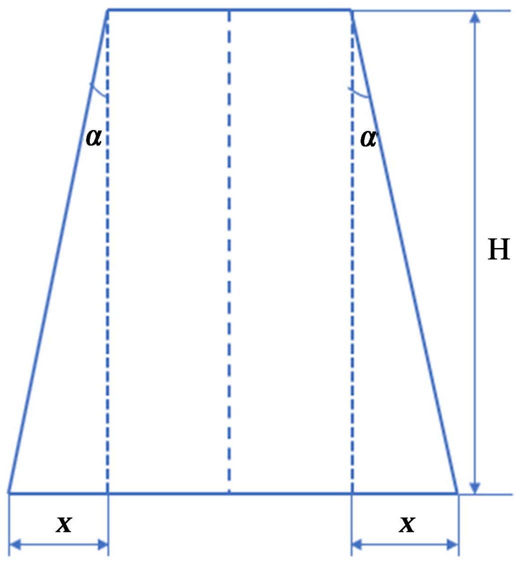

Figure 2. Wheelbase variation principle diagram.

wheelbase is determined. Finally, the method of least squares is used to identify the optimal value of the wheelbase among all those of the selected range. The least squares method is a scatterplot adjustment method which consists in minimizing the squares of the deviations between the theoretical curve and the approximation curve. Excel software is used to obtain a suitable equation of the distribution trend line based on this method. The minimum of the equation obtained is the optimum value sought for the wheelbase. This value is the one for which the cost of the pylon and its foundations is the lowest while ensuring the resistance of the structure.

3. Results and Analysis

3.1. Tower Sizing Results

The characteristics as well as the dimensions of the pylon and its foundations are obtained following the dimensioning. The results of this dimensioning are presented in Table 2.

3.2. Effects of the Wheelbase on the Steel Structure of the Tower

The wheelbase is varied according to the principle shown in Figure 2 from its design value of 8 m obtained following the dimensioning. From 12 m, the displacements of the nodes exceed the acceptable values and the structure is no longer stable. The value of 11.5 m is therefore retained as the upper limit of the wheelbase. The lower limit of the wheelbase is chosen equal to 4 m to limit the instabilities of the structure. The wheelbase variation range is therefore from 4 m to 11.5 m. The graph in Figure 3 shows the effect of the wheelbase on the cost of the metal structure of the pylon. This cost is evaluated for each wheelbase of the selected range and the graph shows the variation in this cost as a function of the wheelbase.

There is an increase of 52.28% in the cost of the pylon between the smallest and the largest value of the wheelbase. The observed increase is explained by the fact that the spacing of the feet of the pylon induces the lengthening of the chords and the increase in their sections. The pylon is then heavier and more expensive. There is, however, a slight decrease in the cost of the pylon between 5 and 5.5 m wheelbase before this value starts to rise again. This fall is explained by reaching the optimum value of the wheelbase for which the cost of the structure

Table 2. Results of tower dimensioning.

Pylon type	Material	Dimensions	Initial wheelbase	Optimal wheelbase	Foundations
X-truss	S355 and S275 steel	Height: 32 m	8 m	6.29 m	Superficial isolated footing type with inclined shaft
Armament triangle	Equal Leg L-Angle	Bracket length: 4 m			
Square cross section	Regular bolts: M18 and M20	Header section: 4 m^2			

is the lowest. But in general, the greater the wheelbase, the higher the weight and cost of the metal structure.

3.3. Effects of the Wheelbase on Foundations

As for the steel structure, the cost of the foundations is evaluated for each wheelbase of the range of values retained.

The graph in **Figure 4** shows the effect of the wheelbase on the cost of the pylon foundations.

From the analysis of the graph it is noted that contrary to that of the structure, the cost of the foundations decreases when the wheelbase increases. A decrease of 69.95% of this cost is observed between the extreme values of the wheelbase. This result remains consistent with the conclusion drawn from the analysis of the forces at the foot of the pylon. Thus, the larger the wheelbase, the smaller the vertical forces at the feet of the pylon and the lighter and more inexpensive the foundations.

3.4. Effects of Wheelbase on the Whole Structure

The graph in **Figure 5** shows the combined effect of the wheelbase both on the

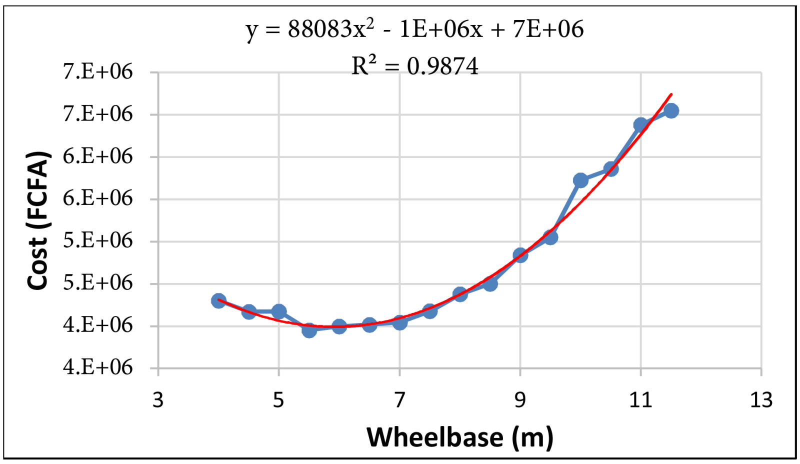

Figure 3. Cost of the steel structure of the pylon as a function of the wheelbase.

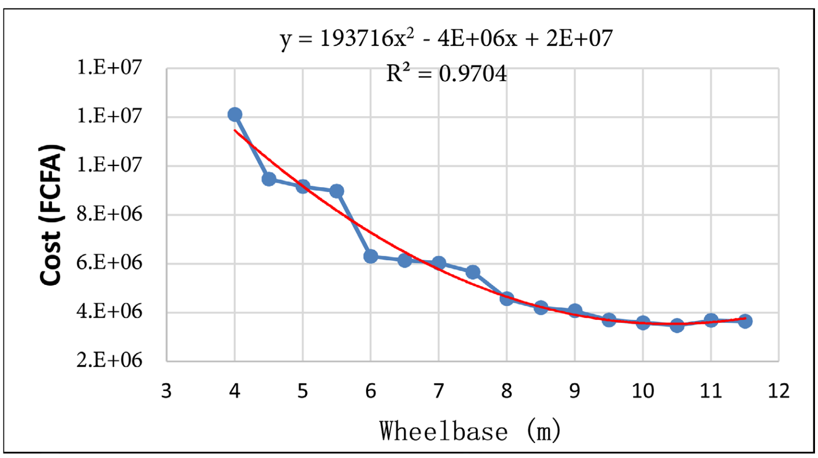

Figure 4. Cost of foundations as a function of the wheelbase.

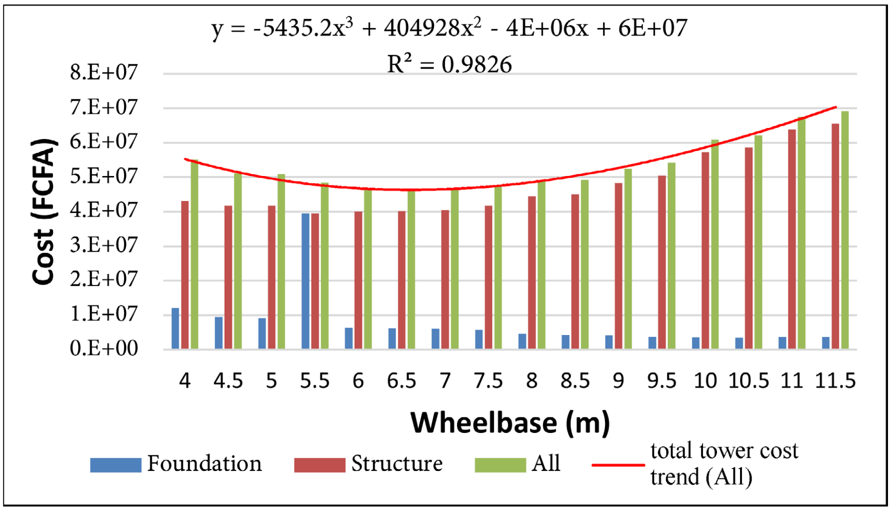

Figure 5. Costs of the structure as a function of the wheelbase.

metal structure and on the foundations of the pylon. A grouped histogram was therefore constructed as well as a polynomial trend curve modeling the cost of the entire structure as a function of the wheelbase. This cost is obtained by adding the cost of the metal structure and that of the foundations for each footing.

From the analysis of the figure, the following conclusions are drawn:

- The cost of the entire work is highly dependent on that of the structure. The shape of the cost of the work is the same as that of the cost of the metal structure of the pylon.
- The cost of the assembly increases as the wheelbase increases. However, the curve has two appearances. One decreases between 4 and 6 m wheelbase, where the cost of the work decreases by 16.06%. Then an ascending zone where this cost increases by 49.43% between 6 and 11.5 m wheelbase. These two distinct speeds are explained by the achievement of the optimum cost value (lowest cost) around 6 m of wheelbase.
- The largest wheelbase (11.5 m) corresponds to the highest cost of the work.
- The lowest cost of the entire work is obtained 6 m wheelbase. The range from 6 m to 7 m wheelbase is where the overall costs are lowest.

3.5. Search for the Optimal Structure

The wheelbase is varied within a range of values ranging from 4 m to 11.5 m and the optimum value retained is that for which the resistance conditions of the work (structure and foundations of the pylon) are satisfied and the cost minimum. In order to confirm the result obtained following the experiment, an analytical method was used. The method of least squares is chosen. By taking the trend curve translating the cost of the entire structure as a function of the wheelbase, this method will make it possible to verify that there is not a value of the wheelbase obtained with a pitch other than 0.5 m and giving a lower cost than previously found. For this, the minimum of the trendline is sought. This curve is shown in **Figure 6**.

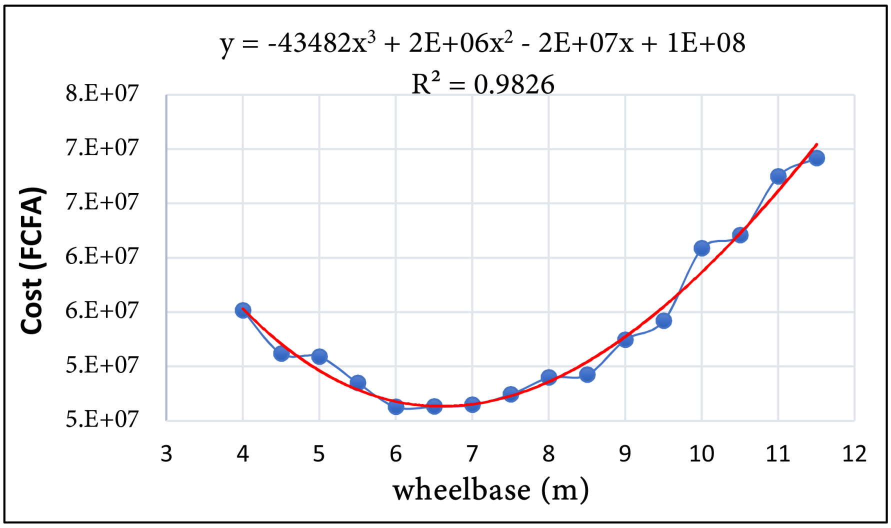

Figure 6. Cost of the structure according to the wheelbase.

Equation (1) is that of the trend curve, obtained with a coefficient of determination $R^2 = 0.9826$.

$$y = -43482x^3 + 2\times10^6 x^2 - 2\times10^7 x + 10^8 \quad (1)$$

After calculation, the optimal value of the wheelbase found is 6.29 m. This value is not very far from the 6 m retained with the experimental values. With this wheelbase value, the cost of the work calculated by using Equation (1) gives the value of 42,507,348.23 FCFA against that of 46,288,053.94 FCFA previously obtained with a 6 m wheelbase. This also represents a saving of 12,639,010 FCFA compared to the cost obtained with 4 m of wheelbase and a saving of 26,659,522 FCFA compared to that obtained for 11.5 m of wheelbase.

4. Conclusion

This work provides a decision support tool, useful to designers whose mission is to size reliable structures to maximize their lifespan and optimize design variables to reduce their cost. Based on the behavior of the structure and foundations of a lattice pylon with triangle armament, under various combinations of loads existing in the Republic of Benin, a range of optimal values of the width at the base of the pylon (footing) is found. These values are optimal because they make it possible both to guarantee the necessary resistance conditions and a minimum cost of the structure. Indeed, by choosing a wheelbase of between 6 and 6.5 m for the pylons, substantial savings can be made in a project like PADSBEE where hundreds of pylons must be built. It is therefore up to the designers to find a compromise between these optimal values of the wheelbase and the constraints of the terrain and the specifications. However, if values between 6 and 6.5 m cannot be retained, then it is preferable to choose small wheelbases (between 4 and 6 m). These lead to a resistant and light metal structure and massive but stable foundations. Such structures are less expensive than those obtained with large wheelbases (between 7 and 11.5 m). However, it is important to emphasize that there are many ways to optimize lattice towers and the modification of a single parameter (type of bracing, arming of the tower, service conditions of the structure, etc.) could lead to different results for ideal wheelbase values. Experimentation must therefore be continued in order to offer experts a wide range of results and tools to best guide the choice of wheelbase.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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List of Acronyms and Abbreviations

CEB: *Electric Community of Benin*

PADSBEE: *Project for Sustainable and Secure Access to Electrical Energy*

Nomenclature

Symbol	Designation	Unit of measurement
a	Angle of inclination of the tower legs to the vertical	°
x	Distance induced by angle a	Metre (m)
H	Height under the bottom bracket of the pylon	Metre (m)

Annex

Annex 1*: List of normative and indicative documents*

CEB standards lines 2010 [13]

IEC 60826 on design criteria for overhead transmission lines [14]

NF EN 50341 relating to overhead power lines with voltage greater than 45 kV in alternating current and rated frequencies less than 100 Hz [15]

EUROCODES 7; Rules for Reinforced Concrete at Limit States (BAEL) 91 revised 99 [16]